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U. S. NAVAL AIR ENGINEERING CENTER

PHILADELPHIA, PENNSYLVANIA

AERONAUTICAL MATERIALS LABORATORY

REPORT NO. NAEC-AML-2187 DATE 30 July 1965

THE EFFECTS OF SHOT PEENING ON THE FATIGUE PROPERTIES OF DAMAGED BARE AND DAMAGED CHROME PLATED HIGH STRENGTH 4340 STEEL

PROBLEM ASSIGNMENT NO. 12-28 UNDER BUREAU OF NAVAL WEAPONS WEPTASK RRMA 02 011/200 1/F020-01-01

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6 THE EFFECTS OF SHOT PEENING ON THE FATIGUE PROPERTIES OF DAMAGED BARE AND DAMAGED CHROME PLATED HIGH STRENGTH 4340 STEEL,

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF PLATES

ABSTRACT

It was determined that shot peening has a significant beneficial effect on the fatigue properties of damaged bare and damaged plated 4340 steel (260 ksi), particularly upon the fatigue life at stresses above the fatigue limit. It was further established that shot peening is more beneficial in recovery of mild damage than it is in the recovery of severe damage. There are indications that shot peening of steel damaged to an extremely severe degree has a further deleterious effect on the fatigue properties of the damaged steel.

I. INTRODUCTION

1. An incidental phase of a previous investigation, reference (a), to study the beneficial effects of shot peening on the fatigue life of chrome plated high strength steel, disclosed that shot peening after plating was just as effective as shot peening before plating. From this limited investigation, it would seem that a very significant practical consideration could be given to the possibility of shot peening plated parts that had been in service and were susceptible to fatigue failure because of reduced fatigue properties due to chrome plating. This could also apply to unplated parts under similar service conditions. Such parts could be removed, shot peened (without stripping plating, if present) and re-installed with a minimum of inconvenience.

2. Reference (b) authorized that a more comprehensive evaluation be made of the effects of shot peening, after plating, on the fatigue life of plated high strength steels (260 to 270 ksi), with particular emphasis on the effects of shot peening on plated and unplated steels subjected to damaging high stresses but not showing surface cracks.

II. EXPERIMENTAL PROCEDURES

1. The material used was from a commercial heat of AISI 4340 steel in accordance with MIL-S-5000A, meeting the chemical requirements shown below, and heat treated to a strength level of 260,000:

Carbon	.38/.43
Manganese	.60/.80
Phosphorus	.040 Max.
Sulphur	.040 Max.
Silicon	.20/.35
Nickel	1.65/2.0
Chromium	.70/.90
Molybdenum	.20/.30

2. The fatigue evaluation was conducted on an R. R. Moore Rotating Beam Fatigue Testing Machine using standard smooth specimens with a test diameter of 0.250". The specimens were prepared in the following manner:

   a. Pieces were cut to exact length and turned to ½" diameter on centers;

   b. Re-centered with controlled depth - drilled and tapped both ends;

   c. Identification stenciled on both ends;

d. Heat treated - normalized at 1600°F for 30 minutes, austenitized at 1525°F for one hour, oil quenched and then tempered for one hour at 630°F;

e. Rough ground to 0.025" oversize;

f. Finish ground center section to 0.008" oversize;

g. Finish ground center section to 0.002" oversize - depth of cut not exceeding 0.001";

h. Ground tapers;

i. Polished by hand longitudinally, using the following successively finer grades of abrasive to give an RMS finish of not greater than 10 microinches:

Emery Carborundum, No. 180
TRI-M-ITE Silicon Carbon Paper, Grit No. 400A
Emery Polishing Paper, No. 0
Emery Polishing Paper, No. 4/0

3. Shot-peened specimens were peened in an airless blast machine, using S-110 heat treated steel shot to produce uniform coverage having an arc height of A2-0.009 to 0.010".

4. Specimens were chrome plated at a current density of 2 amperes/ square inch for two hours. The ratio of chromic acid to sulphate in the chromium plating bath was 100 to 1; 33 ounces of chromic acid to the gallon was used. The bath temperature was maintained at 131°F ± 1°, with air agitation. These plating conditions resulted in a plating thickness of 0.002", with a tolerance of -0.0001" + 0.

5. The basic fatigue evaluation consisted of establishing S-N curves, damage lines, and the evaluation of damage before and after shot peening, for each of four groups of specimens representing the metal in four conditions, as follows:

Bare, unpeened
Bare, peened
Plated
Plated and peened

6. Damage lines were established in the classical manner, working from a conventional S-N curve determined by using all virgin specimens. A number of virgin specimens were then pre-stressed, each at a different specific stress above the fatigue limit but for the same number of cycles, representing a fraction of the normal life at these pre-stresses for the virgin material. These specimens were then re-tested at the

fatigue limit established by the virgin S-N curve. Those that failed were presumed to have been damaged by the pre-stress, whereas those that did not fail were assumed to have no damage incurred. From these pre-stressed specimens, it could be determined at what life the pre-stress had no damaging effect on the fatigue limit. Several other specimens, pre-stressed at other stresses and at another cycle level, determined another stress-cycle combination at which no damage was inflicted. A line drawn through a series of such stress-life combinations is somewhat facetiously called a "damage line". Thus, any specimen pre-stressed at any combination of life and stress below the damaged line is said to be undamaged (if the effects on the fatigue limit is denoted as the damage criteria). This does not necessarily mean that the pre-stressed specimens were not damaged with respect to the same or higher test level.

7. Additional confirmation as to the location of the damage line was obtained by damaging groups of specimens in the established damage area, with different degrees of damage (same value of pre-stress but with increasing number of stress cycles, approaching fracture). Groups of damaged specimens, consisting of specimens each damaged to the same degree within the group, but varying in magnitude from group to group, were evaluated for damage by subjecting the damaged specimens to a fixed intermediate test stress, until failure occurred. The remaining life, as compared to the life of the virgin specimen, was taken as a measure of damage. In addition, one-half of the specimens were shot peened and re-tested at the same intermediate test stress, to ascertain, by comparison, what effects shot peening had on the damaged material. Other groups of damaged specimens were re-tested, after shot peening, at the same test stress as the pre-stress, thus determining by direct comparison, the effects of shot peening on the damaged material.

8. In order to investigate the feasibility of re-peening service damaged parts (either plated or unplated) which had been previously shot peened during the fabrication process, a similar evaluation was done with peened and plated-peened groups, except that fewer degrees of damage were examined in each case.

9. If information concerning the complete damage behavior of a part is desired, a more rational and comprehensive method is to establish a complete S-N curve for the damaged test pieces. For this purpose, two groups of identical specimens were subjected to damage, each to one of two degrees of damage (severe and moderate), for the bare and plated specimens. These two groups of damaged specimens were treated as new test pieces with probable different fatigue properties, and new S-N curves were established and compared with S-N curves obtained with virgin test pieces. Similarly damaged specimens were shot peened and S-N curves were established for comparison with S-N curves of unpeened damaged specimens to ascertain what effects, if any, shot peening had on damaged

specimens. This was also done on a lesser scale with the peened and plated-peened groups of specimens, by evaluating only one degree of damage, again to investigate the potential effect of a second peening procedure.

10. It is a well known fact that remarkable increases in fatigue properties may be obtained by the "coaxing process". The coaxing process involves repeated under-stressing for a large number of cycles at a level just below the fatigue limit, followed by a few million cycles at each of a series of higher stresses, increased in gradual steps. Not much work has been published on the effect of coaxing on the fatigue properties of chrome plated steel. In order to obtain some data which would be of academic interest and possible future practical use, a few bare and chrome plated specimens were subjected to the coaxing process for limited comparison.

11. In all further discussions in this report, it will be understood that fatigue limit values are based on 20 million cycles of stress, and fatigue strengths, where used as comparison hereinafter, are based on 100,000 cycles of stress.

12. All damage reported herein was confined to the early stages prior to the formation of visible surface cracks detectable by dye penetrant inspection methods. This was the case no matter how severe the damage appeared to be, short of complete fracture.

13. As an aid to discussion relative to fatigue damage behavior, the terms "cycle ratio" and "damage ratio" will be used extensively in this report. The cycle ratio is defined as the ratio of the number of pre-stress cycles at a designated pre-stress level to the expected virgin life at that pre-stress (n_p/N_p). The cycle ratio is a rather elementary but convenient method of indicating the fractional fatigue life used up at any given pre-stress level. The measure of damage caused by the pre-stress is expressed by the damage ratio, which is defined as the ratio of the difference between the number of cycles at the expected virgin life at the test stress and the life of the damaged material to the expected virgin life (N_t-n_t/N_t). Curves of cycle ratio vs damage ratio, based on test data, are used in this report to characterize damage behavior of the bare and plated steel at different stress levels.

III. RESULTS

1. The S-N curves and damage lines for each of the four conditions investigated - bare (control), peened, plated and plated-peened - are shown on Plate 1, giving a composite picture of the fatigue behavior. The usual amount of scatter was obtained, but in the interest of clarity, the individual test plot points are not shown on the graph. The detailed raw data from which these curves were established is shown in Table 1.

2. The fatigue limits and the fatigue strengths, together with comparison of the values of each group to its control, are summarized below:

	Fatigue Limit		Fatigue Strength	
	ksi	%	ksi	%
Bare, unpeened (control)	96	---	130	---
Bare, peened	103	107.3	154	118.5
Plated	66	68.8	90	69.2
Plated-peened	104	108.3	142	109.2

3. The effect of shot peening on the fatigue life of bare specimens damaged to various degrees is shown graphically on Plate 2, listed in detail in tabular form in Table 2, and is summarized below:

BARE STEEL

High Stress Level Damage

Pre-stressed at 135 ksi for the cycle ratio indicated and then re-tested at 120 ksi.

Cycle Ratio	Damage Ratio	Life, Kilocycles* Unpeened	Life, Kilocycles* Peened	Improvement Ratio
0.02	0.56	119.0	1,365.7	11.5
0.05	0.66	93.0	958.3	10.3
0.30	0.73	74.0	756.0	10.2
0.50	0.79	57.3	592.0	10.3
0.80	0.84	44.0	11.7	0.3

*Represents the average life of three specimens, but the number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

Pre-stressed at 135 ksi for the cycle ratios indicated, shot peened and then re-tested at the same stress as the pre-stress, for direct comparison:

Cycle Ratio	Life, Kilocycles Virgin Specimens	Life, Kilocycles* Peened Specimens	Improvement Ratio
0.02	60	324.0	5.4
0.30	60	241.0	4.0
0.80	60	9.7	0.2

Low Stress Level Damage

Pre-stressed at 105 ksi for the cycle ratios indicated and then re-tested at 120 ksi.

Cycle Ratio	Damage Ratio	Life, Kilocycles* Unpeened	Peened	Improvement Ratio
0.3	0.28	195.3	2,734.7	14.0
0.5	0.35	176.7	2,249.7	12.7
0.7	0.41	159.3	1,714.0	10.8

*Represents the average life of three specimens, but the number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

4. The above analytical data (involving re-testing at other than the pre-stress level) is shown in pictorial form on Plates 3 and 4, for the high stress and low stress damage levels, respectively. A composite picture of the damage behavior of the bare steel at different cycle ratios is presented on Plate 5.

5. Comparisons of related S-N curves of severely damaged and moderately damaged bare steel, unpeened and peened, are shown graphically on Plates 6 and 7, respectively, the data for which is listed in Table 3. A summary of the values is shown below:

BARE STEEL

	Fatigue Limit		Fatigue Strength	
	ksi	%	ksi	%
Bare (Control)	96	---	130	---
Peened	103	107.3	154	118.5
Severely Damaged*	90	93.8	108	83.1
Severely Damaged, Peened	98	102.1	134	103.1
Moderately Damaged**	95	99.0	122	93.8
Moderately Damaged, Peened	98	102.1	141	108.5

*Severely Damaged at 135 ksi for 30 kc for a Cycle Ratio of 0.5 and a Damage Ratio of 0.79

**Moderately Damaged at 135 ksi for 3 kc for a Cycle Ratio of 0.5 and a Damage Ratio of 0.66

6. The effect of shot peening on the fatigue life of plated specimens damaged to various degrees is shown graphically on Plate 8, listed in detail in tabular form on Table 4, and summarized below:

PLATED STEEL

High Stress Level Damage

Pre-stressed at 100 ksi for the cycle ratios indicated and then re-tested at 90 ksi.

		Life, Kilocycles*		
Cycle Ratio	Damage Ratio	Unpeened	Peened	Improvement Ratio
0.02	0.50	50.0	20,000**	400 plus
0.10	0.57	42.7	20,000**	468 plus
0.20	0.62	38.0	81.0	2.1
0.50	0.79	21.0	45.7	2.2
0.70	0.90	9.7	19.7	2.0
0.80	0.96	4.3	2.7	0.6

*Represents the average life of three specimens, but the number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

**Indicates one or more specimens had run-out life of 20 million cycles.

Pre-stressed at 100 ksi for the cycle ratios indicated, shot peened and then re-tested at the same stress as the pre-stress, for direct comparison.

Cycle Ratio	Life, Kilocycles Virgin Specimens	Life, Kilocycles* Peened Specimens	Improvement Ratio
0.1	50	1,211.0	24.2
0.2	50	267.0	5.3
0.5	50	75.7	1.5
0.8	50	7.3	0.2

Low Stress Level Damage

Pre-stressed at 70 ksi for the cycle ratios indicated and then re-tested at 90 ksi.

Cycle Ratio	Damage Ratio	Life, Kilocycles* Unpeened	Peened	Improvement Ratio
0.4	0.29	71.3	20,000**	280 plus
0.5	0.36	64.0	15,737**	246 plus
0.6	0.43	57.0	14,801**	260 plus
0.8	0.56	44.3	10,798**	244 plus

*Represents the average life of three specimens, but the number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

**Indicates one or more specimens had run-out life of 20 million cycles.

7. The above analytical data is shown in pictorial form on Plates 9 and 10, for the high and low stress levels, respectively. A composite picture of the damage behavior of the plated steel at different cycle ratios is presented on Plate 11.

8. Comparisons of related S-N curves of severely and moderately damaged plated steel, unpeened and peened, are shown graphically on Plates 12 and 13, respectively, the data for which is listed in Table 5. A summary of values is shown below:

PLATED STEEL

	Fatigue Limit		Fatigue Strength	
	ksi	%	ksi	%
Plated	66	---	90	---
Plated and Peened	104	157.6	142	157.8
Plated, Severely Damaged*	34	51.5	38	42.2
Plated, Severely Damaged, Peened	50	75.8	72	80.0
Plated, Moderately Damaged**	65	98.5	85	94.4
Plated, Moderately Damaged, Peened	98	148.5	116	128.9

*Severely Damaged at 100 ksi for 35 kc for a Cycle Ratio of 0.7 and a Damage Ratio of 0.9
**Moderately Damaged at 100 ksi for 5 kc for a Cycle Ratio of 0.1 and a Damage Ratio of 0.57

9. A summary of the effect on the fatigue limit and fatigue strength is shown graphically on Plates 14 and 15, respectively, and is listed below:

BARE STEEL

	Fatigue Limit/ksi		Fatigue Strength/ksi	
Damage Ratio	Unpeened	Peened	Unpeened	Peened
0	96	103	130	154
0.66	95	98	122	141
0.79	90	98	108	134

PLATED STEEL

	Fatigue Limit/ksi		Fatigue Strength/ksi	
Damage Ratio	Unpeened	Peened	Unpeened	Peened
0	66	104	90	142
0.57	65	98	85	116
0.90	34	50	38	72

10. The effect of repeening on the fatigue life of the bare peened specimens at two degrees of damage is shown graphically on Plate 16, listed in detail in tabular form in Table 16, and summarized below:

BARE, SHOT PEENED STEEL

Pre-stressed at 135 ksi for the cycle ratios indicated and then re-tested at 120 ksi.

Cycle Ratio	Damage Ratio	Life, Kilocycles* Peened	Life, Kilocycles* Re-Peened	Improvement Ratio
0.09	0.83	455.0	462.3	1.0
0.62	0.97	87.3	59.3	0.7

*Represents the average life of three specimens, but the number of cycles of pre-stress that caused damage is not included in the number of cycles sustained by the specimens at the test stress.

Shot peening again after damage did not show any basic improvement in the fatigue life of the previously peened specimens, so all further investigation was discontinued, since there appeared to be no practical use for this type application.

11. The effect of repeening on the fatigue life of the plated-peened specimens at three different degrees of damage is shown on Plate 17, listed in detail in tabular form in Table 7, and summarized below:

PLATED, SHOT PEENED STEEL

Pre-stressed at 135 ksi for the cycle ratios indicated and then re-tested at 120 ksi.

Cycle Ratio	Damage Ratio	Life, Kilocycles* Peened	Life, Kilocycles* Re-Peened	Improvement Ratio
0.10	0.71	436.7	467.3	1.1
0.14	0.98	25.7	17.3	0.7
0.60	0.99	10.0	5.7	0.6

*Represents the average life of three specimens, but the number of cycles of pre-stress that caused damage is not included in the number of cycles sustained by the specimens at the test stress.

As in the case of the bare peened steel, because there was no appreciable improvement in the fatigue life as a result of shot peening again, after damage, the investigation concerning repeening of plated-peened specimens was discontinued as being of no significant practical consequence.

12. For emphasis, it is repeated that in all cases listed above, the number of cycles that caused damage are not included in the number of cycles sustained by the specimens at the test stress. In other words, each damaged specimen, whether unpeened or peened, was treated as a new specimen when evaluated and compared to another.

13. The increase in failure stress (by coaxing) for both the bare and plated steels is shown on Plates 18 and 19, respectively, the graphs of which are self-explanatory.

IV. ANALYSIS OF RESULTS

1. The damage lines as developed, and as shown on Plate 1, are rather cursory in nature but are adequate for the purpose intended. No attempt was made to precisely pin-point the damage lines; rather they were established primarily to determine general areas of damage for the purpose of associating detectable quantitative degrees of damage with the hoped-for beneficial effects of shot peening on damaged material. Since the establishment of the damage lines was incidental to the main area of investigation, it was not deemed feasible to investigate complete damage behavior at extremely high loads and low cycle life. However, it is believed that if the damage lines were accurately determined along the entire range of life, each damage line would have a tendency to curve upward and theoretically intersect its virgin S-N curve at some point corresponding to the ultimate strength and one cycle of stress, where damage would be complete.

2. The composite picture of all the S-N curves and their corresponding damage lines, as shown on Plate 1, for the four conditions investigated (bare, bare peened, plated and plated-peened) makes for interesting analysis.

3. Prior tests (reference (b)) of a different heat of 4340 steel at 260 ksi strength level, resulted in an increase in fatigue limit of the bare steel from 98 ksi to 102 ksi when shot peened, as compared to 96 ksi to 103 ksi, respectively, obtained in the investigation reported herein, using the same shot peening technique and, just as before, the beneficial effects were more pronounced at the higher test stress levels. The above values of the fatigue limits correlate rather favorable, considering the fact that different heats of steel were used, and that tests were conducted at different times of the year in a fatigue laboratory having neither temperature nor humidity control. The improvement in fatigue life, because of shot peening, is a result of compressive residual stresses on the surface introduced by cold work, and the degree of improvement in most cases is generally related to the susceptibility of the steel to strain hardening. The surface compressive stresses cause

the location of crack nuclei to be shifted to some point below the surface, which reduces the harmful effect of surface stress raisers. Shot peening, in addition, nullifies the stress concentration effects of surface imperfections which are ever present to a more or less degree and which are incipient sources for fatigue failures. Significantly, the damage line of the bare peened metal is located closer to its S-N curve; indicating the bare metal is more susceptible to early damage than peened metal.

4. The relationship of the bare steel S-N curve to its damage line is similar to that of the plated steel S-N curve to its damage line, except that the plated steel curves are displaced downward and to the left for lowered fatigue characteristics. This would seem to indicate that the chromium plating had the effect of lowering both the fatigue limit and the finite life, and maintaining more or less the same relative area of damage. The reduction in fatigue properties of the plated steel is quite significant, particularly in the case of the fatigue limit, which was reduced from 96 ksi to 66 ksi for the plated steel, an amount equal to 31.2%. This reduction in the fatigue properties of the plated steel is due to the fact that (1) the chrome plating itself contains internal cracks which act as severe stress raisers and (2) the chrome is electrodeposited in a tensile stress condition, which has further adverse effects on the fatigue properties of plated steels, especially in bending applications.

5. As a result of shot peening, the fatigue limit of the plated steel was raised from 66 ksi to 104 ksi, representing an approximate increase of 8% over the 96 ksi fatigue limit of the bare steel. Thus, shot peening not only improved the reduced fatigue life of the plated steel, but it increased it above that of the bare steel. It is interesting to note that the fatigue limit of the peened plated steel (104 ksi) was approximately equal to that of the peened bare steel (103 ksi), the slight difference being well within the range of experimental error. Of great significance is the fact the damage line of the plated steel was moved upward (by shot peening) until it almost corresponded with the damage line of the peened bare metal. Thus, the shot peening of plated steel not only restored to the steel its original fatigue properties prior to plating, but it significantly reduced the vast damage area shown on the damage S-N curve plot, which indicates the elimination of much of the early potential damage associated with plated steels.

6. The increase of the fatigue properties of the plated steel, by shot peening, is attributed mainly to the beneficial effects of the shot peening process which has a tendency to round off and peen over the many sharp macroscopic cracks that are generally present in a standard electrodeposited chromium plating, thus minimizing the harmful stress concentration effects of these plating cracks. In addition to this, shot

peening places the plating in a state of compressive residual stress and compacts the surface of the plating, and perhaps some of the shot peening effect is transmitted through the chrome plating to the basis metal, all conditions which tend to hinder the formation and propagation of tensile fatigue cracks.

7. An examination of Plates 2, 3, and 4 clearly demonstrates the obvious beneficial effects of shot peening on the fatigue life of bare steel damaged to various degrees, except for the one case where the damage was so severe (0.84 damage ratio) that shot peening adversely effected the fatigue life. At damage ratios less than 0.8, the bare damaged steel showed an improvement in fatigue life as high as 11 times for severely damaged bare steel, and 18.5 times for moderately damaged steel. The composite picture of the damage behavior of the bare steel at different cycle ratios, shown on Plate 5, indicates that a simple linear relationship between damage and cycle ratio does not exist.

8. Comparison of full S-N curves of unpeened damaged and peened damaged bare steel, for severe and moderate damage, Plates 6 and 7, respectively, showed improvements (as a result of shot peening) both in finite life and fatigue life for both degrees of damage, to the extent that in both cases the fatigue limits of the peened damaged steel were greater than the fatigue limits of the unpeened virgin steel. Substantiating this, R. L. Jones, reference (c), established that shot peening was effective in extending fatigue life of 4335M steel specimens, heat treated to 260-280 ksi ultimate strength, which had been cyclic stressed to 60% of their life expectancy. R. F. Brodrick, reference (d), found that shot peening of propeller blades made of 4340 steel acted as a barrier to the detrimental effects of subsequent surface damage, such that specimens which were peened before damage showed an average fatigue limit of 110% higher than those which were not shot peened prior to damage.

9. Evidence on Plates 8, 9, and 10 conclusively demonstrate the great beneficial effects of shot peening on the fatigue life of plated steel damaged to various degrees. This was particularly apparent at the high stress level damage ratios of 0.50 and 0.57, where the improvement in fatigue life was at least 400 times or more. However, at the high stress level damage ratios of between 0.62 and 0.90, the improvement was only twice as great. At the low stress level damage (damage ratios less than 0.60), the damaged plated steel consistently showed an improvement in fatigue life of at least 244 times or more. As in the case of the bare steel, plated stee' hat had been damaged at a very severe level (0.96 damage ratio) show further adverse effects when shot peened. Plated steel behaved in a manner similar to the behavior of bare steel in that there was no evidence of a linear relationship between cycle ratio and damage ratio, Plate 11, although the damage seemed to be less when retested at a test stress less than the pre-stress.

10. Comparison of full S-N curves of plated damaged unpeened and plated damaged peened steel for severe and moderate damage, Plates 12 and 13, show improvement (as a result of shot peening) in both finite life and fatigue limit, but not to the extent exhibited by the damaged bare steel. In the case of the bare steel, the general fatigue properties of the damaged material were significantly improved by shot peening to the point that they were superior to those of the undamaged steel. In contrast to this, only the moderately damaged plated steel (when peened) showed fatigue properties superior to the undamaged unpeened plated steel. Although showing some improvement, the fatigue properties of the severely damaged plated peened steel did not approach those of the undamaged unpeened plated steel.

11. The beneficial effects of shot peening on the fatigue characteristics of damaged bare steel and plated damaged steel is attributable to the same factors that cause beneficial effects on the undamaged bare and undamaged plated steels, as stated elsewhere in this report. It must be borne in mind that the damage inflicted had not reached the visible crack stage when evaluated. It is doubtful if shot peening would have significant beneficial effects if visible cracks had been formed - shot peening does not perform a welding action to heal over cracks. Rather, shot peening, in the presence of fatigue cracks, would perhaps aggravate the situation to cause more damage and thus shorten fatigue life. The presence of visible cracks would mean the accumulation of irreparable damage.

12. An examination of Plates 14 and 15 discloses that fatigue limits and fatigue strengths of the steel in bare, peened, plated and plated-peened conditions were not appreciably affected until the damage ratio exceeded 0.6, indicating that damage of a moderate nature, even though occurring early in the fatigue process, was not necessarily critical. Of particular interest was the case of the bare and the bare peened steel, where even at the severe damage ratio of 0.79 the fatigue properties were not too drastically reduced. In contrast to this, the plated and the plated-peened steel had fatigue properties markedly reduced at the fatigue damage ratios greater than 0.6.

13. An analysis of the evaluation pertaining to the questionable beneficial effects of shot peening a second time after damage (either of the bare or plated steel), revealed that at mild damage there was little or no beneficial effect, whereas at severe damage levels, there was a decided deleterious effect on the fatigue properties as a result of the second shot peening.

14. The increase in fatigue properties of the 4340 steel by the "coaxing process" has been suggested as being due to work hardening of the metal. This explanation has been rejected by G. M. Sinclair, reference (f), who points out that fatigue cracks usually are formed in the

very regions which should have been work-hardened the most. Rather, it is believed that the beneficial coaxing effects appears to be associated with the phenomenon of strain aging (increase in elastic properties as a result of a rest period after straining a small amount) which is common in many ferrous metals. Results of Sinclair's investigation indicate that "those metals which had a matrix of ferrite capable of further strain-aging had their fatigue resistance improved by the coaxing procedure. The metals which were work-hardenable but which had little or no capacity for strain-aging (or for further aging) showed no coaxing effect".

15. After enough data had been generated to substantiate the belief that the coaxing process did have a beneficial effect on the fatigue properties, further investigational work was discontinued, since it was not the prime objective of this phase of the problem assignment. However, it is believed there is sufficient interest and promise in this area to warrant a comprehensive investigation of the mechanism and beneficial effects of the coaxing process on the fatigue properties of the more commonly used steels in aircraft construction.

16. Basically, there are at least three different stages involved in the fatigue process: (1) crack nucleation; (2) formation and development of microcracks; and (3) rapid crack propagation and failure.

17. In the first stage, unfavorably oriented crystals are deformed under load so that relative sliding motion of atoms along crystallographic shear planes produce slip bands. Slip is further aggravated by a pile-up of dislocations in the crystal lattice, and by imperfections such as voids and inclusions. Under repeated loading, new slip bands are continually forming parallel to the original bands since the metal in the vicinity of the earlier slip bands has been strain hardened and resists further slippage, except at higher stresses. Most slip bands start to form during the first few thousand cycles of stress and continue to form during the first stage, but not too any great extent in the second and third stages.

18. The second stage takes place when continued cycling causes the coalescence of a number of crack nuclei associated with slip bands to form submicroscopic cracks. These submicroscopic cracks form early during the finite fatigue life, and may take up the largest portion of the fatigue life. The number of these cracks formed depend upon the stress; many at high stress, few at low stress.

19. The third stage is the combining of a number of submicroscopic cracks to form either one or more macrocracks in the direction perpendicular to the maximum tensile stress, whose growth to some critical length is cause for sudden fracture in a relatively short time.

20. During the first stage of the fatigue process, slip takes place in favorable crystal planes and directions to produce localized yielding with associated strain hardening which tends to improve fatigue resistance in these localized areas. A residual stress field is associated with this slip which can impose a damaging preload on crystal planes with limited slip capability which is aggravated by non-metallic inclusions and second phase particles which create stress concentration and an associated weakening effect, leading to subsequent formation of submicroscopic cracks and ultimate failure with repeated loading. There is enough justification to believe that both tendencies, one strengthening and the other weakening, may be occurring during the fatigue process, with strengthening predominant at low stress levels and damage at high stress levels. It may well be that the fatigue limit of a steel is that stress at which an equilibrium is reached between the damage occurring at localized discontinuities, and strengthening due to strain aging.

21. It is assumed that the damage described herein occurred either in the first or second stage of the fatigue process, depending upon the cycle ratio used to establish the damage, since there appeared to be no surface cracks in any case of the damage noted during this investigation. To re-iterate, experimental evidence indicates that nuclei of fatigue damage form early in the fatigue process and the number of crack nuclei formed in the relatively early life depends upon the stress level and number of cycles. It also must be recognized that the distribution of damage in a single specimen is a varying quantity depending upon the lack of homogeneity of the material. Low pre-stress cycles will affect comparatively few regions susceptible to crack nucleation, whereas high pre-stress cycles will not only increase the number of crack nuclei, but will also effect the existing crack nuclei in a more intensive measure. Thus, it may be stated that the amount of damage initiated in a material is a function of the number of cycles and the pre-stress level, not necessarily a linear function.

22. Retesting at a higher test stress has a tendency to extend and enlarge the damage mainly at the crack nuclei already formed, rather than to create additional crack nuclei. The converse is probably true - retesting at a lower stress tends to create additional crack nuclei slowly, rather than to quickly propagate damage already present as a result of the lower pre-stress. In all cases of latent fatigue damage, the rate at which crack nuclei propagate is a function of the magnitude of the test stress.

23. In the case of the S-N curve of the severely damaged material, crack nuclei have coalesced sufficiently to form submicroscopic cracks of critical lengths during the pre-stress, which grow into visible cracks upon subsequent testing to establish new S-N curves with much lower fatigue properties both for the finite life and the fatigue limit. In the case of the S-N curves of the mildly damaged materials, the crack nuclei have not progressed to the point of submicroscopic crack formation, so that additional cycling is required to increase the damage enough to cause formation of submicroscopic cracks, thus resulting in extended life and fatigue limit, as compared to the severely damaged materials.

24. Those damage nuclei which have reached some critical stage during the pre-stress will promote premature failure upon being stressed at the fatigue limit of the virgin material (using the fatigue limit as a damage criteria). The life of the pre-stressed specimens, compared to the run-out life of the virgin specimens, is some indication of the magnitude of the damage inflicted by the pre-stress. It has been found that this measure of damage depends entirely upon the test stress used, since the damaging treatment may produce a reduced fatigue life at one stress level and an increased life at still another.

25. It must be emphasized that the scope of this investigation was exploratory in nature and this limitation precluded the use of a large number of specimens to give significant statistical meaning to the results. However, other investigators, reference (e), in making comparisons of statistical tests with those reported in non-statistical investigations, have come to the conclusion that non-statistical investigations of the effect of fatigue damage on fatigue life are, in general, believed to be fairly reliable.

V. CONCLUSIONS

The results of this investigation demonstrate conclusively that shot peening has a significant beneficial effect on the fatigue properties of damaged bare and damaged plated 4340 steel (260 ksi), particularly upon the fatigue life at stresses above the fatigue limit. The amount of improvement depends upon the degree of damage - the greater the damage the less the improvement, with a tendency for shot peening to have an adverse effect on the fatigue life under extremely severe damage conditions.

A greater degree of recovery was experienced in shot peening damaged bare steel than in shot peening damaged plated steel, although at the moderately damaged condition the damaged plated steel showed spectacular improvement in fatigue life, much more so than was the case for the moderately damaged bare steel.

No beneficial effects were noted, by shot peening after damage, in the fatigue properties of damaged bare steel and damaged plated steel that had been previously shot peened prior to damage.

Experimental evidence indicates the following to be true concerning cumulative damage of 4340 steel:

a. Fatigue damage forms early in the total life of the fatigue process;

b. Initiation and amount of damage by a pre-stress above the fatigue limit is a function of the number of cycles as well as the magnitude of the pre-stress;

c. Damage is not a linear function of the pre-stress; additional cycles of over-stress produce greater proportional damage;

d. Pre-stressing caused a consistent reduction in fatigue properties; although at damage ratios of less than 0.6 the reduction is not considered significant.

VI. RECOMMENDATIONS

It is recommended that consideration be given to the possibility of shot peening particular bare or plated 4340 steel parts (previously unpeened) that have been in service in a given aircraft model and start to fail by a fatigue mechanism, taking into account other factors such as dimensional changes and surface finish requirements.

It is further recommended that the authorization of additional problem assignments be initiated for a more comprehensive statistical study of the following facets of high strength aircraft steels, both in the bare and plated conditions, listed in order of priority:

a. Cumulative damage and fatigue behavior;

b. Beneficial effects of shot peening on the fatigue properties of damaged steel;

c. Determination of optimum pre-stressing procedures for maximum "coaxing effect".

REFERENCES

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(c) R. L. Jones; Methods of Predicting and/or Improving Materials Fatigue Life; Convair Report No. FGT-2096; October 1962

(d) R. F. Brodrick; Protective Shot Peening of Propellers; WADC Report 55-56, Part II; August 1955

(e) G. E. Dieter, G. T. Horne and R. F. Mehl; Statistical Study of Over-stressing in Steel; NACA TN 3211; July 1954

(f) G. M. Sinclair; An Investigation of the Coaxing Effect in Fatigue of Metals; ASTM Preprint 92 (1952)

FATIGUE DATA FOR ESTABLISHING S-N CURVES AND DAMAGE LINES OF BARE STEEL, SHOT PEENED STEEL, PLATED STEEL, AND PLATED-PEENED STEEL

BARE METAL (CONTROL) S-N Curve		SHOT PEENED METAL S-N Curve	
Stress/ksi	Cycles	Stress/ksi	Cycles
140	55,000	140	375,000
130	83,000	130	648,000
120	202,000	120	2,840,000
110	256,000	115	6,860,000
105	981,000	110	7,452,000
100	3,547,000	108	14,048,000
99	4,526,000	105	16,283,000
98	1,856,000	104	14,262,000
97	2,088,000	103	20,000,000*
96	20,000,000*	103	35,000,000*
96	20,000,000*		

Damage Line			Damage Line		
Pre-Stress ksi	Pre-Stress kc	Kilocycles at 96 ksi Retest	Pre-Stress ksi	Pre-Stress kc	Kilocycles at 103 ksi Retest
110	3	3,157	140	10	20,000*
109	3	20,000*	142	10	20,000*
108	10	274	145	10	5,687
106	10	16,424	135	40	20,000*
105	10	20,000*	137	40	1,565
103	50	12,018	127	150	985
102	50	20,000*	125	150	20,000*
99	200	1,563	124	400	14,282
98	200	20,000*	122	400	20,000*
			110	2000	20,000*
			113	2000	11,276
			112	2000	8,420

*Indicates No Failure

TABLE 1

PLATED METAL
S-N Curve

Pre-Stress/ksi	Cycles
120	16,000
110	32,000
100	42,000
90	94,000
80	160,000
70	586,000
68	728,000
67	452,000
66	20,000,000*
66	20,000,000*

PLATED AND PEENED METAL
S-N Curve

Pre-Stress/ksi	Cycles
150	76,000
140	102,000
130	450,000
120	769,000
115	1,940,000
110	4,042,000
108	7,470,000
105	17,937,000
104	20,000,000*
104	20,000,000*

Damage Line

Pre-Stress		Kilocycles at
ksi	kc	66 ksi Retest
85	3	203
84	3	20,000*
80	10	627
78	10	20,000*
76	30	340
75	30	20,000*
74	70	84
73	70	428
71	70	20,000*
70	70	20,000*

Damage Line

Pre-Stress		Kilocycles at
ksi	kc	140 ksi Retest
130	50	20,000*
131	50	20,000*
132	50	4,500
125	150	20,000*
127	150	11,250
122	300	20,000*
123	300	1,668
119	600	270
117	600	20,000*

*Indicates No Failure

TABLE 1

FATIGUE DATA - EFFECT OF SHOT PEENING ON DAMAGED BARE STEEL AT VARIOUS DEGREES OF DAMAGE

High Stress Level Damage - Pre-stressed at 135 ksi for the cycle ratios indicated and then retested at 120 ksi.

	1,200 Cycles (C.R.-0.02) Retest Cycles*		3,000 Cycles (C.R.-0.05) Retest Cycles*		18,000 Cycles (C.R.-0.3) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened	Unpeened	Peened
	155,000	1,227,000	159,000	801,000	65,000	805,000
	77,000	1,393,000	63,000	920,000	77,000	689,000
	125,000	1,477,000	57,000	1,154,000	88,000	775,000
Avg.	119,000	1,365,667	93,000	958,333	74,000	756,333
	I.R. = 11.5		I.R. = 10.3		I.R. = 10.2	

	30,000 Cycles (C.R.-0.5) Retest Cycles*		48,000 Cycles (C.R.-0.8) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened
	52,000	652,000	45,000	7,000
	76,000	354,000	39,000	6,000
	44,000	770,000	48,000	22,000
Avg.	57,333	592,000	44,000	11,667
	I.R. = 10.3		I.R. = 0.27	

- -

C.R. = Cycle Ratio = Pre-stress cycles/Virgin life cycles

I.R. = Improvement Ratio = Cycles of Peened Specimens/Cycles of Unpeened Specimens

Life at 135 ksi is 60 kc.
Life at 120 ksi is 270 kc.
Life at 105 ksi is 1,200 kc.

*The number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

<u>High Stress Level Damage</u> - Pre-stressed at 135 ksi for the cycle ratios indicated, then shot peened and retested at the same stress as the pre-stress, 135 ksi.

1,200 Cycles (C.R.-0.02) Retest Cycles*	18,000 Cycles (C.R.-0.3) Retest Cycles*	48,000 Cycles (C.R.-0.8) Retest Cycles*
367,000	222,000	10,000
330,000	157,000	6,000
275,000	344,000	13,000
Avg. 324,000	Avg. 241,000	Avg. 9,667
I.R. = 5.4	I.R. = 4.0	I.R. = 0.16

<u>Low Stress Level Damage</u> - Pre-stressed at 105 ksi for the cycle ratios indicated and then retested at 120 ksi.

	360,000 Cycles (C.R.-0.3) Retest Cycles*		600,000 Cycles (C.R.-0.5) Retest Cycles*		840,000 Cycles (C.R.-0.7) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened	Unpeened	Peened
	210,000	2,808,000	155,000	2,732,000	186,000	1,603,000
	186,000	2,904,000	185,000	2,018,000	160,000	1,554,000
	190,000	2,492,000	190,000	2,999,000	132,000	1,985,000
Avg.	195,333	2,734,667	175,667	2,249,667	159,333	1,714,000
	I.R. = 14.0		I.R. = 12.7		I.R. = 10.8	

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C.R. = Cycle Ratio = Pre-stress cycles/Virgin life cycles

I.R. = Improvement Ratio = Cycles of Peened Specimens/ Cycles of Unpeened Specimens

Life at 135 ksi is 60 kc.
Life at 120 ksi is 270 kc.
Life at 105 ksi is 1,200 kc.

*The number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

TABLE 3

FATIGUE DATA FOR ESTABLISHING S-N CURVES - SEVERELY AND MODERATELY DAMAGED BARE STEEL

Undamaged and Unpeened (Control) — Undamaged and Peened

See Table 1 for this data

Severely Damaged (135 ksi x 30 kc)			Moderately Damaged (135 ksi x 3 kc)		
	Cycles**			Cycles**	
Stress/ksi	Unpeened	Peened	Stress/ksi	Unpeened	Peened
140	24,000	55,000	140	19,000	139,000
130	34,000	103,000	130	50,000	279,000
120	57,000	592,000	120	93,000	958,000
110	89,000	2,326,000	110	248,000	6,003,000
105	---	1,442,000	105	1,458,000	---
100	66,000	1,128,000	101	---	6,223,000
99	---	2,503,000	100	496,000	11,580,000
98	---	20,000,000*	99	---	9,456,000
95	272,000	29,700,000	98	---	20,000,000*
92	208,000		96	3,590,000	
91	973,000		95	20,000,000*	
90	20,000,000*				

*Indicates No Failure

**The number of cycles of pre-stress that caused damage are not included in the lives of either the unpeened or peened specimens.

FATIGUE DATA - EFFECTS OF SHOT PEENING ON DAMAGED PLATED STEEL AT VARIOUS DEGREES OF DAMAGE

High Stress Level Damage - Pre-stressed at 100 ksi for the cycle ratios indicated and then retested at 90 ksi.

	1,000 Cycles (C.R.-0.02) Retest Cycles*		5,000 Cycles (C.R.-0.1) Retest Cycles*		10,000 Cycles (C.R.-0.2) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened	Unpeened	Peened
	48,000	20,000,000**	35,000	20,000,000**	37,000	87,000
	52,000	20,000,000**	47,000	20,000,000**	31,000	85,000
	50,000	20,000,000**	46,000	20,000,000**	46,000	71,000
Avg.	50,000	20,000,000	42,667	20,000,000	38,000	81,000
	I.R. = 400 or more		I.R. = 468 or more		I.R. = 2.1	

	25,000 Cycles (C.R.-0.5) Retest Cycles*		35,000 Cycles (C.R.-0.7) Retest Cycles*		40,000 Cycles (C.R.-0.8) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened	Unpeened	Peened
	19,000	44,000	9,000	9,000	3,000	3,000
	21,000	46,000	9,000	16,000	4,000	2,000
	23,000	47,000	11,000	34,000	6,000	3,000
Avg.	21,000	45,667	9,667	19,667	4,333	2,667
	I.R. = 2.2		I.R. = 2.0		I.R. = 0.62	

High Stress Level Damage - Pre-stressed at 100 ksi for the cycle ratios indicated, then shot peened and retested at the same stress as the pre-stress, 100 ksi.

	5,000 Cycles (C.R.-0.1) Retest Cycles*	10,000 Cycles (C.R.-0.2) Retest Cycles*
	1,113,000	310,000
	1,018,000	275,000
	1,502,000	216,000
Avg.	1,211,000	267,000
	I.R. = 24.2	I.R. = 5.34

TABLE 4

High Stress Level Damage - Pre-stressed at 100 ksi for the cycle ratios indicated, then shot peened and retested at the same stress as the pre-stress, 100 ksi. (Continued)

	25,000 Cycles (C.R.-0.5) Retest Cycles*	40,000 Cycles (C.R.-0.8) Retest Cycles*
	75,000	3,000
	100,000	7,000
	52,000	12,000
Avg.	75,667	7,333
	I.R. = 1.5	I.R. = 0.15

Low Stress Level Damage - Pre-stressed at 70 ksi for the cycle ratios indicated and then retested at 90 ksi.

	160,000 Cycles (C.R.-0.4) Retest Cycles*		200,000 Cycles (C.R.-0.5) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened
	74,000	20,000,000**	60,000	20,000,000**
	61,000	20,000,000**	64,000	7,210,000
	79,000	20,000,000**	68,000	20,000,000**
Avg.	71,333	20,000,000	64,000	15,736,667
	I.R. = 280 and more		I.R. = 246 and more	

	240,000 Cycles (C.R.-0.6) Retest Cycles*		320,000 Cycles (C.R.-0.8) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened
	64,000	4,431,000	40,000	20,000,000**
	52,000	20,000,000**	48,000	3,557,000
	55,000	20,000,000**	45,000	8,836,000
Avg.	57,000	14,810,000	44,333	10,797,667
	I.R. = 260 and more		I.R. = 244 and more	

C.R. = Cycle Ratio = Pre-stress cycles/Virgin life cycles
I.R. = Improvement Ratio = Cycles of Peened Specimens/Cycles of Unpeened Specimens

Life at 100 ksi is 50 kc.
Life at 90 ksi is 100 kc.
Life at 70 ksi is 400 kc.

*The number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

**Indicates No Failure

FATIGUE DATA FOR ESTABLISHING S-N CURVES - SEVERELY AND MODERATELY DAMAGED PLATED STEEL

Undamaged, Plated and Unpeened   Undamaged, Plated and Peened

See Table 1 for this data

Severely Damaged (100 ksi x 35 kc)			Moderately Damaged (100 ksi x 5 kc)		
	Cycles**			Cycles**	
Stress/ksi	Unpeened	Peened	Stress/ksi	Unpeened	Peened
120	3,000	7,000	150	---	21,000
100	7,000	20,000	140	---	22,000
90	10,000	26,000	130	---	37,000
80	10,000	85,000	120	12,000	33,000
70	13,000	100,000	110	10,000	184,000
65	24,000	89,000	100	115,000	261,000
60	124,000	320,000	99	---	1,114,000
55	22,000	214,000	98	---	20,000,000*
52	---	1,014,000	90	101,000	
50	25,000	20,000,000*	80	120,000	
40	179,000		70	320,000	
35	14,948,000		67	950,000	
34	20,000,000*		66	710,000	
			65	20,000,000*	

*Indicates No Failure

**The number of cycles of pre-stress that caused damage are not included in the lives of either the unpeened or peened specimens.

TABLE 5

FATIGUE DATA - EFFECT OF SHOT PEENING ON DAMAGED PEENED BARE STEEL AT VARIOUS DEGREES OF DAMAGE

Pre-stressed at 135 ksi for the cycle ratios indicated and then retested at 120 ksi.

	60,000 Cycles (C.R.-0.09)		400,000 Cycles (C.R.-0.62)	
	Retest Cycles*		Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened
	178,000	845,000	98,000	84,000
	967,000	223,000	76,000	29,000
	220,000	319,000	88,000	65,000
Avg.	455,000	462,333	87,333	59,333
	I.R. = 1.0		I.R. = 0.7	

C.R. = Cycle Ratio = Pre-stress cycles/Virgin life cycles

I.R. = Improvement Ratio = Cycles of life of specimens peened second time/ Cycles of life of specimens peened once

Life of peened specimens at 135 ksi is 650 kc.
Life of peened specimens at 120 ksi is 2,700 kc.

*The number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

TABLE 6

FATIGUE DATA - EFFECT OF SHOT PEENING ON DAMAGED PLATED PEENED STEEL AT VARIOUS DEGREES OF DAMAGE

Pre-stressed at 135 ksi for the cycle ratios indicated and then retested at 120 ksi.

	25,000 Cycles (C.R.-0.10) Retest Cycles*		35,000 Cycles (C.R.-0.14) Retest Cycles*	
	Unpeened	Peened	Unpeened	Peened
	180,000	310,000	23,000	17,000
	910,000	842,000	30,000	17,000
	220,000	250,000	24,000	18,000
Avg.	436,667	467,333	25,667	17,333
	I.R. = 1.1		I.R. = 0.67	

	150,000 Cycles (C.R.-0.60) Retest Cycles*	
	Unpeened	Peened
	8,000	6,000
	13,000	7,000
	9,000	4,000
Avg.	10,000	5,667
	I.R. = 0.57	

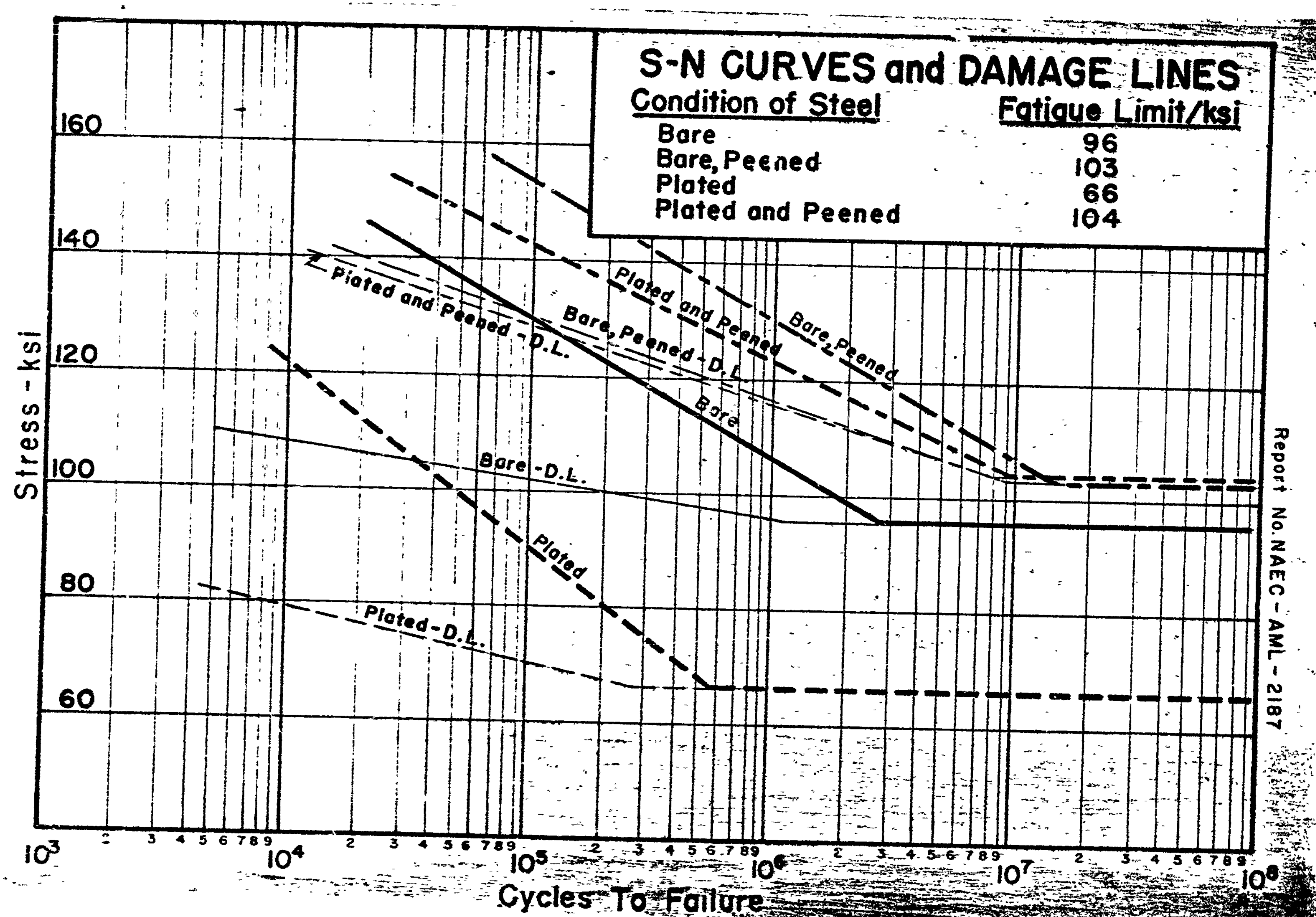
C.R. = Cycle Ratio = Pre-stress cycles/Virgin life cycles

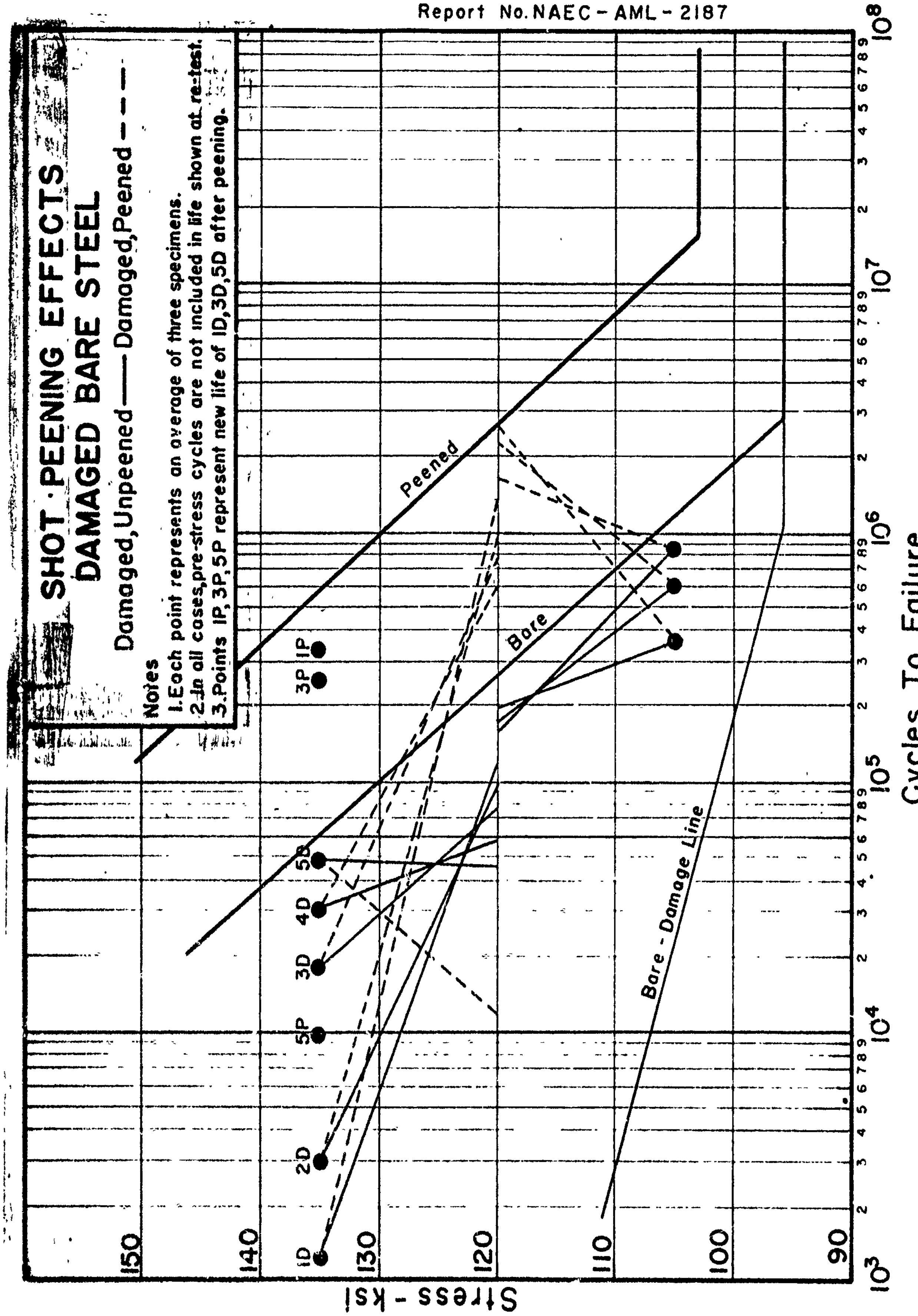
I.R. = Improvement Ratio = Cycles of life of specimens plated and peened second time/Cycles of life of specimens peened once.

Life of plated peened specimens at 135 ksi is 250 kc.
Life of plated peened specimens at 120 ksi is 1,500 kc.

*The number of cycles of pre-stress that caused damage are not included in the number of cycles sustained by the specimens at the test stress.

TABLE 7


S-N CURVES and DAMAGE LINES
Condition of Steel
Fatigue Limit/ksi
Bare 96
Bare, Peened 103
Plated 66
Plated and Peened 104
Stress - ksi
160
140
120
100
80
60
Cycles To Failure
Plated and Peened - D.L.
Bare, Peened - D.L.
Plated and Peened
Bare, Peened
Bare
Bare - D.L.
Plated
Plated - D.L.


SHOT PEENING EFFECTS
DAMAGED BARE STEEL
Damaged, Unpeened —— Damaged, Peened - - -
Notes
1. Each point represents an average of three specimens.
2. In all cases, pre-stress cycles are not included in life shown at re-test.
3. Points 1P, 3P, 5P represent new life of 1D, 3D, 5D after peening.
Peened
Bare
Bare - Damage Line
1D
2D
3D
4D
5D
1P
3P
5P
Stress - KSI
150
140
130
120
110
100
90
Cycles To Failure
10^3
10^4
10^5
10^6
10^7
10^8

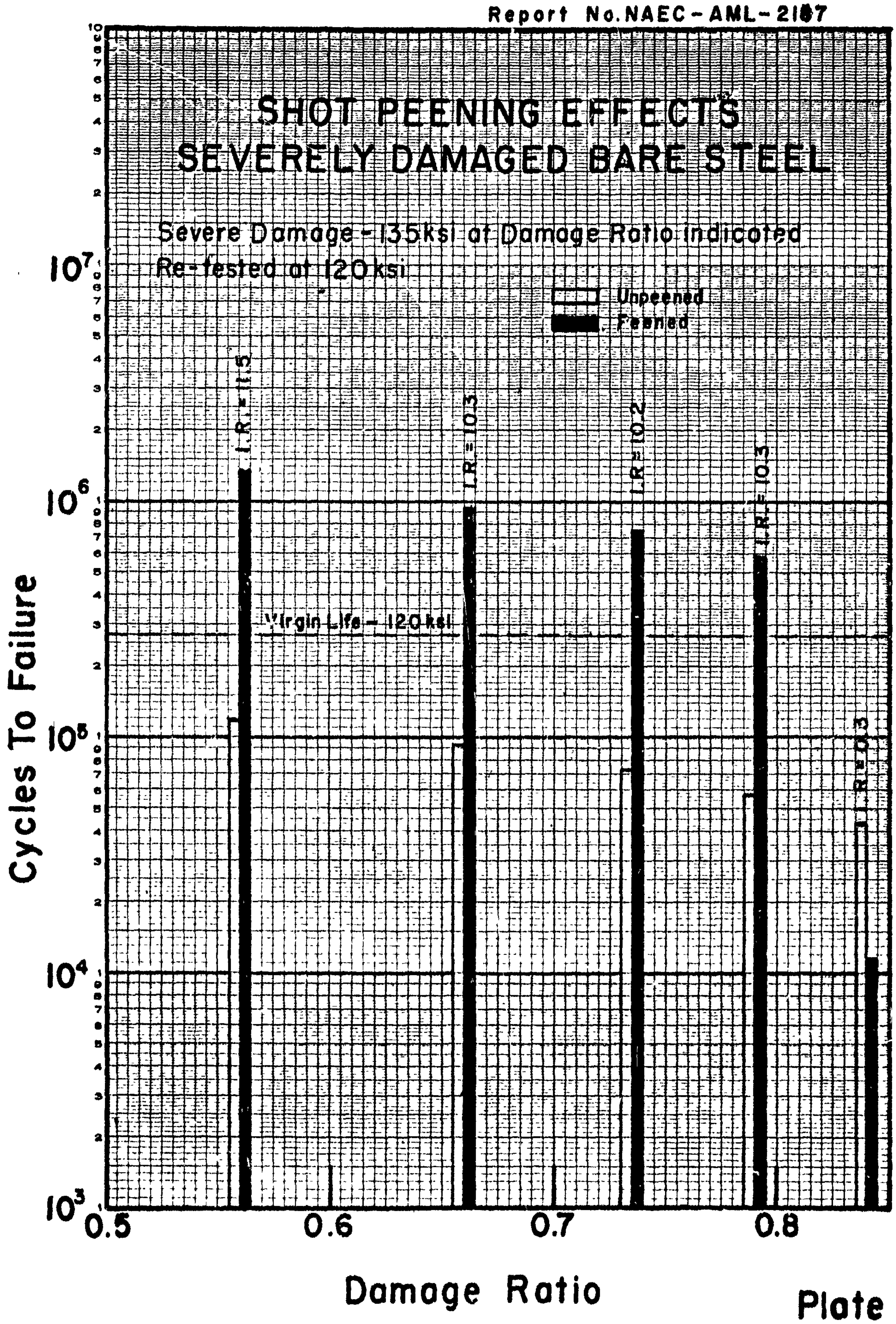

SHOT PEENING EFFECTS
SEVERELY DAMAGED BARE STEEL
Severe Damage - 135ksi at Damage Ratio Indicated
Re-tested at 120ksi
Unpeened
Peened
I.R.=11.5
I.R.=10.3
I.R.=10.2
I.R.=10.3
I.R.=0.3
Virgin Life - 120ksi
Cycles To Failure
10^7
10^6
10^5
10^4
10^3
0.5
0.6
0.7
0.8
Damage Ratio

Plate 3

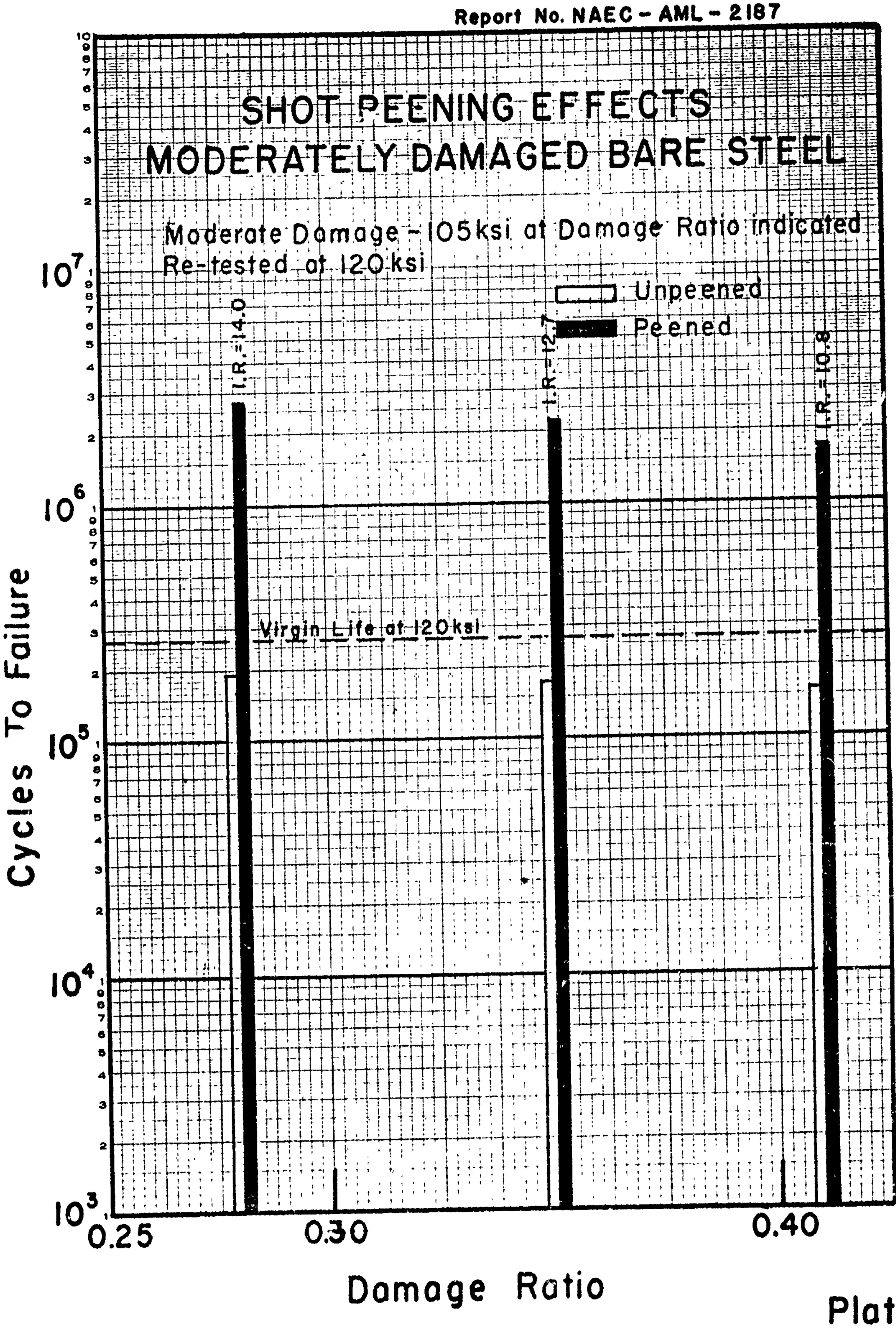
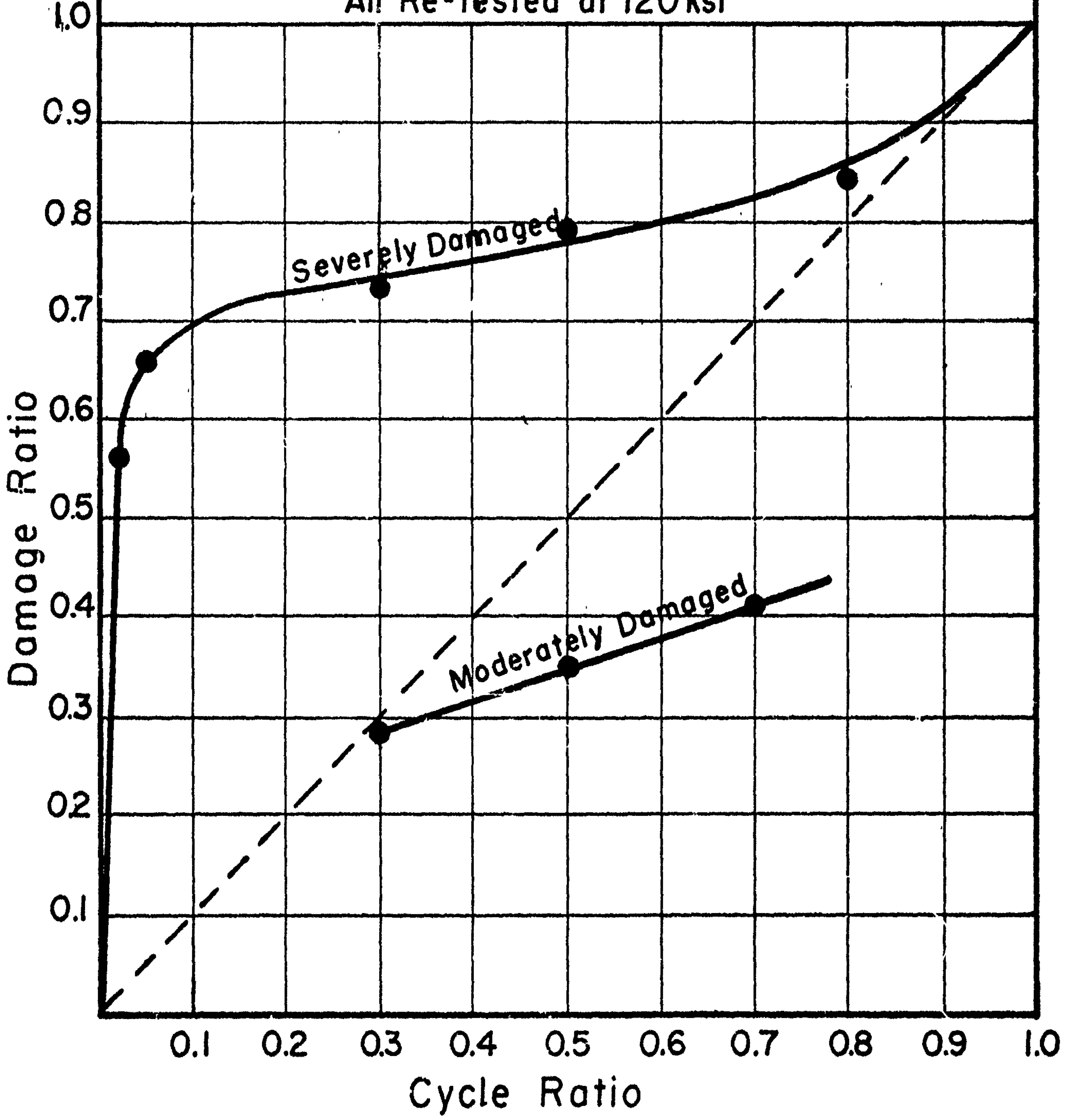
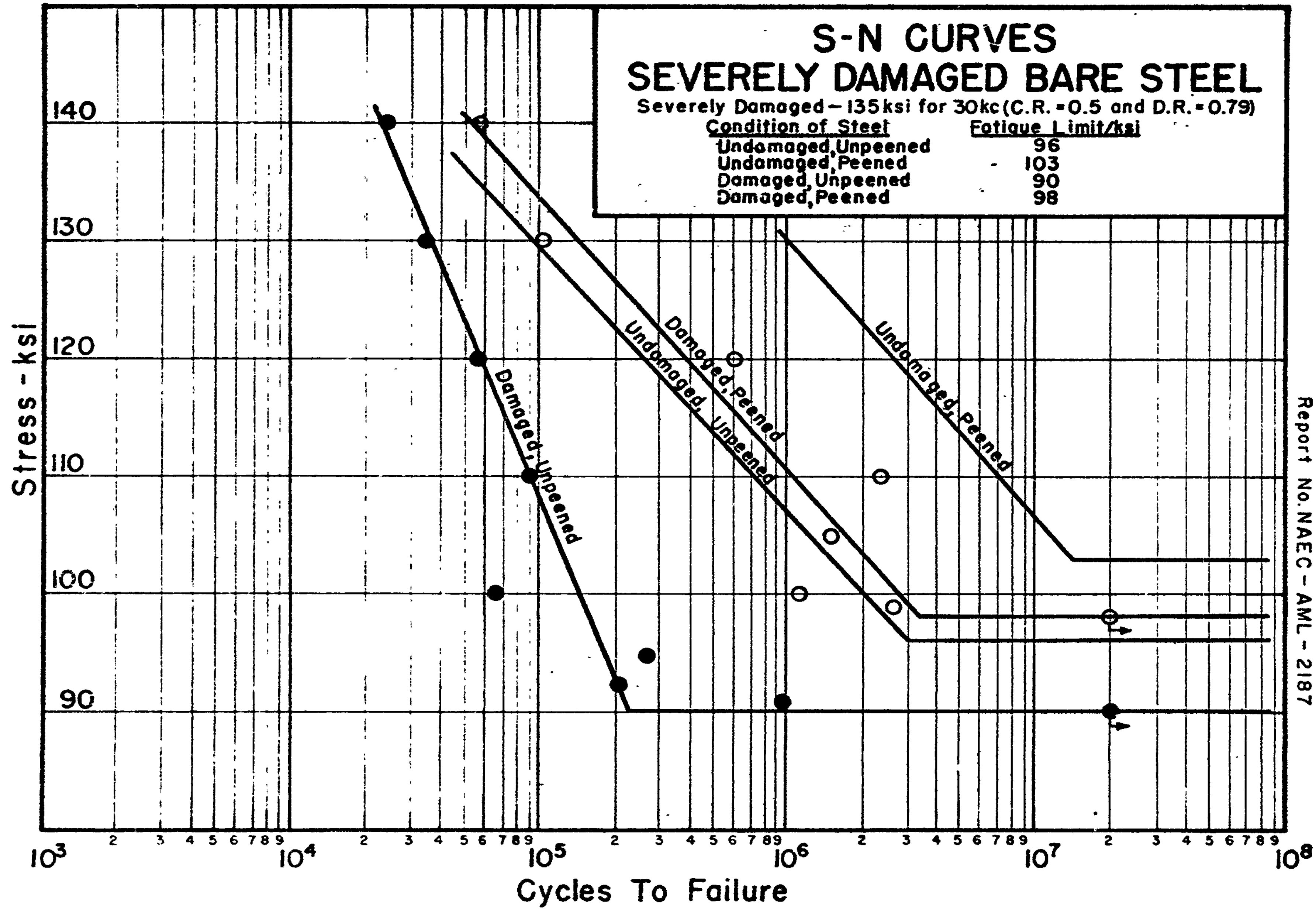

SHOT PEENING EFFECTS
MODERATELY DAMAGED BARE STEEL
Moderate Damage - 105 ksi at Damage Ratio indicated
Re-tested at 120 ksi
Unpeened
Peened
I.R. = 14.0
I.R. = 12.7
I.R. = 10.8
Virgin Life at 120 ksi
Cycles To Failure
10^7
10^6
10^5
10^4
10^3
0.25
0.30
0.40
Damage Ratio

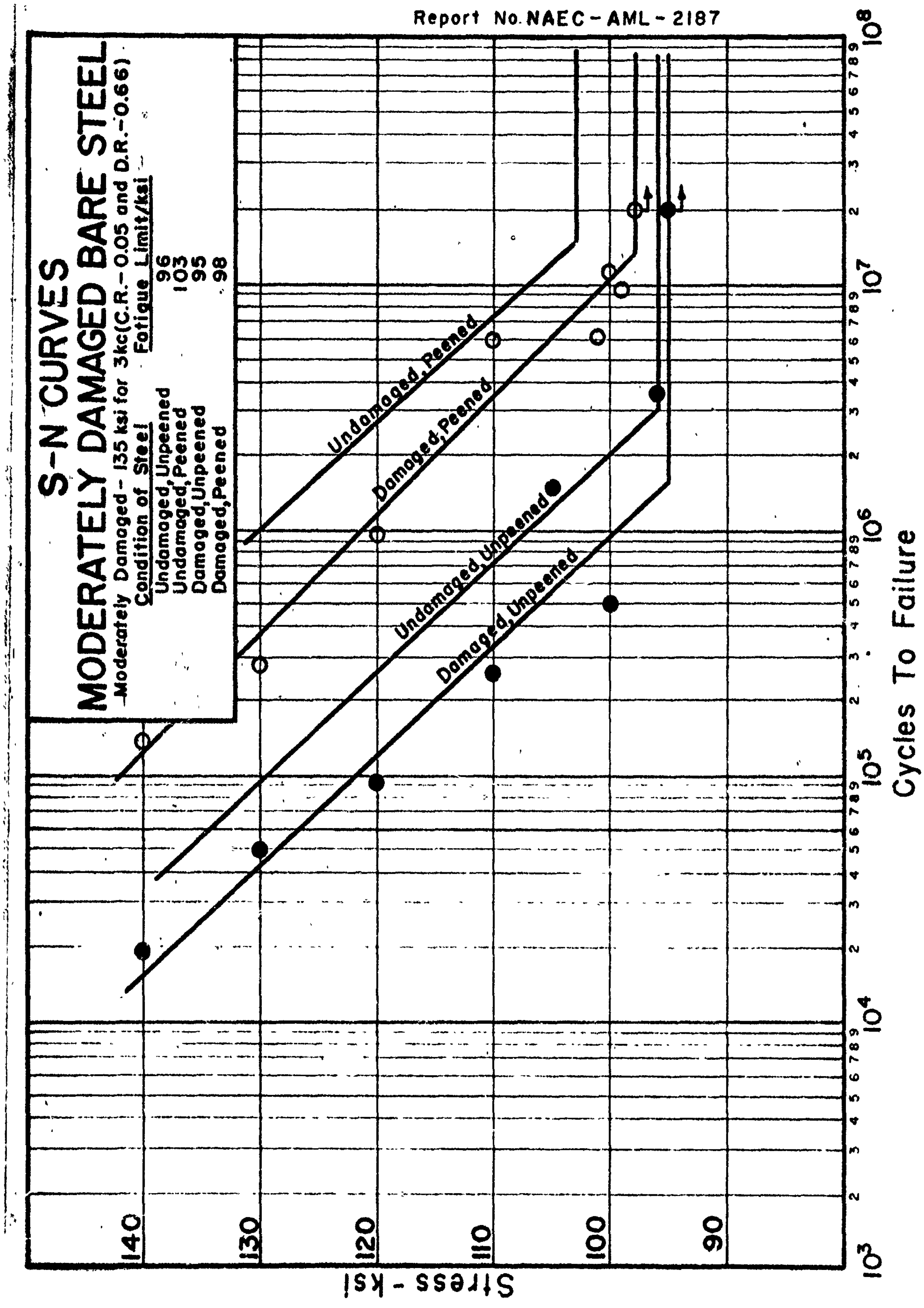
Plate 4

CYCLE RATIO vs DAMAGE RATIO
BARE STEEL

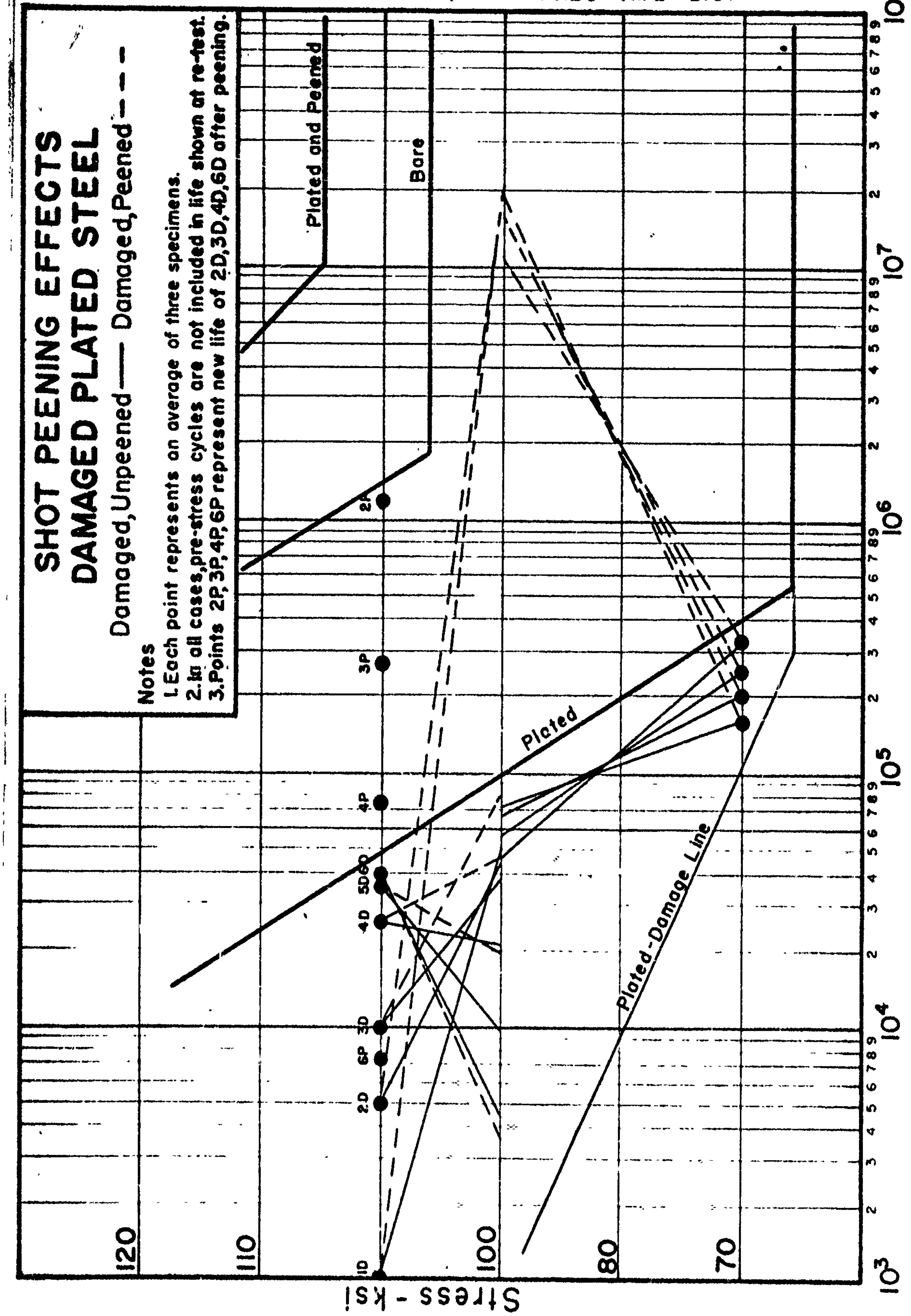
Severely Damaged, Pre-stressed at 135 ksi
Moderately Damaged, Pre-stressed at 105 ksi
All Re-tested at 120 ksi




S-N CURVES
SEVERELY DAMAGED BARE STEEL
Severely Damaged - 135ksi for 30kc (C.R. = 0.5 and D.R. = 0.79)
Condition of Steel
Fatigue Limit/ksi
Undamaged, Unpeened 96
Undamaged, Peened 103
Damaged, Unpeened 90
Damaged, Peened 98
Damaged, Unpeened
Undamaged, Unpeened
Damaged, Peened
Undamaged, Peened
Stress - ksi
140
130
120
110
100
90
Cycles To Failure
10^3
10^4
10^5
10^6
10^7
10^8



S-N CURVES
MODERATELY DAMAGED BARE STEEL
Moderately Damaged - 135 ksi for 3kc(C.R.-0.05 and D.R.-0.66)
Condition of Steel | Fatigue Limit/ksi
Undamaged, Unpeened 96
Undamaged, Peened 103
Damaged, Unpeened 95
Damaged, Peened 98
Undamaged, Peened
Damaged, Peened
Undamaged, Unpeened
Damaged, Unpeened
Stress - ksi
140
130
120
110
100
90
Cycles To Failure
10^3
10^4
10^5
10^6
10^7
10^8


SHOT PEENING EFFECTS
DAMAGED PLATED STEEL
Damaged, Unpeened —— Damaged, Peened - - -
Notes
1. Each point represents an average of three specimens.
2. In all cases, pre-stress cycles are not included in life shown at re-test.
3. Points 2P, 3P, 4P, 6P represent new life of 2D, 3D, 4D, 6D after peening.
Plated and Peened
Bare
Plated
Plated-Damage Line
1D
2D
6P
3D
4D
5D6D
4P
3P
2P
120
110
100
80
70
Stress - ksi
10^3
10^4
10^5
10^6
10^7
10^8
Cycles To Failure

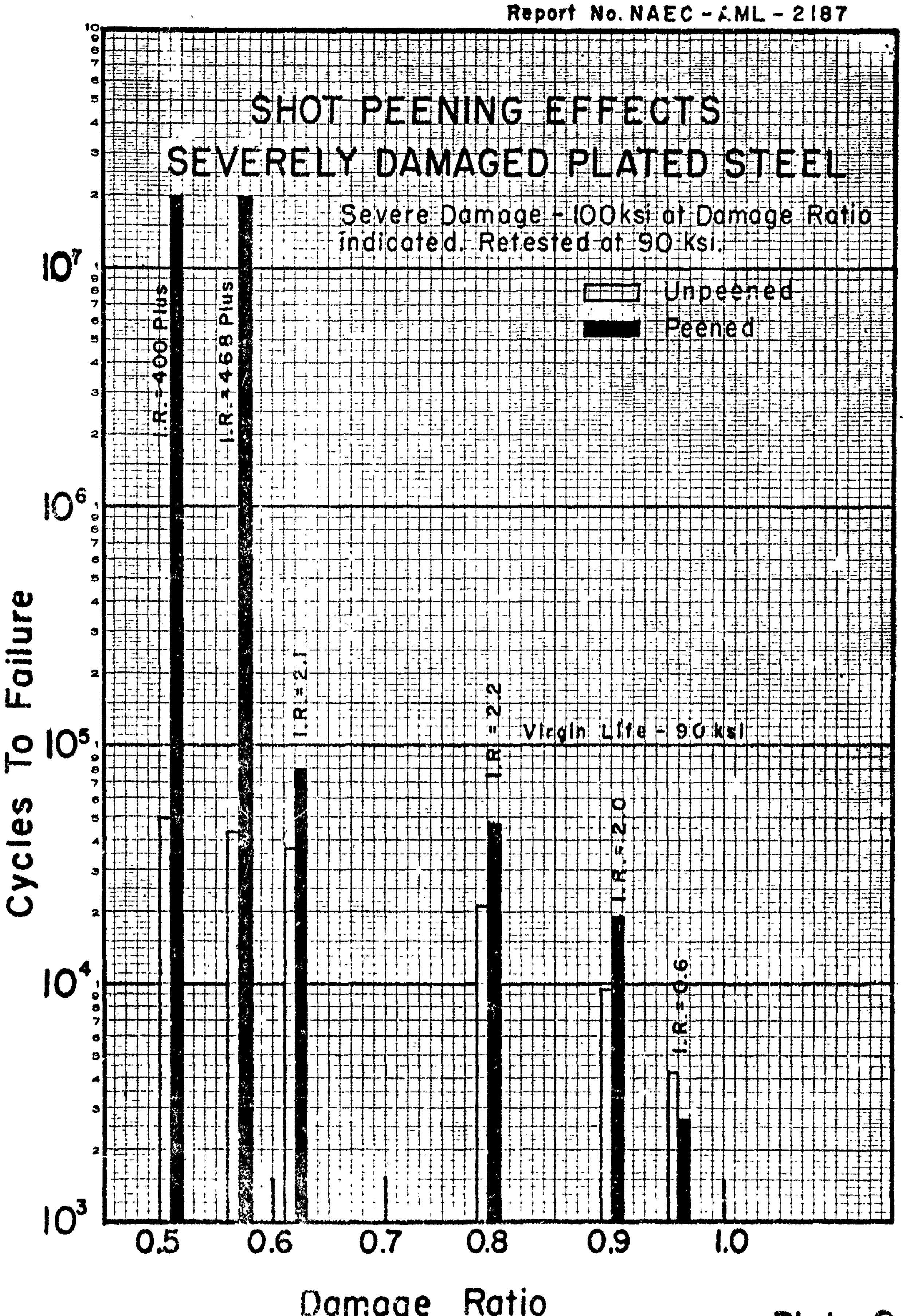
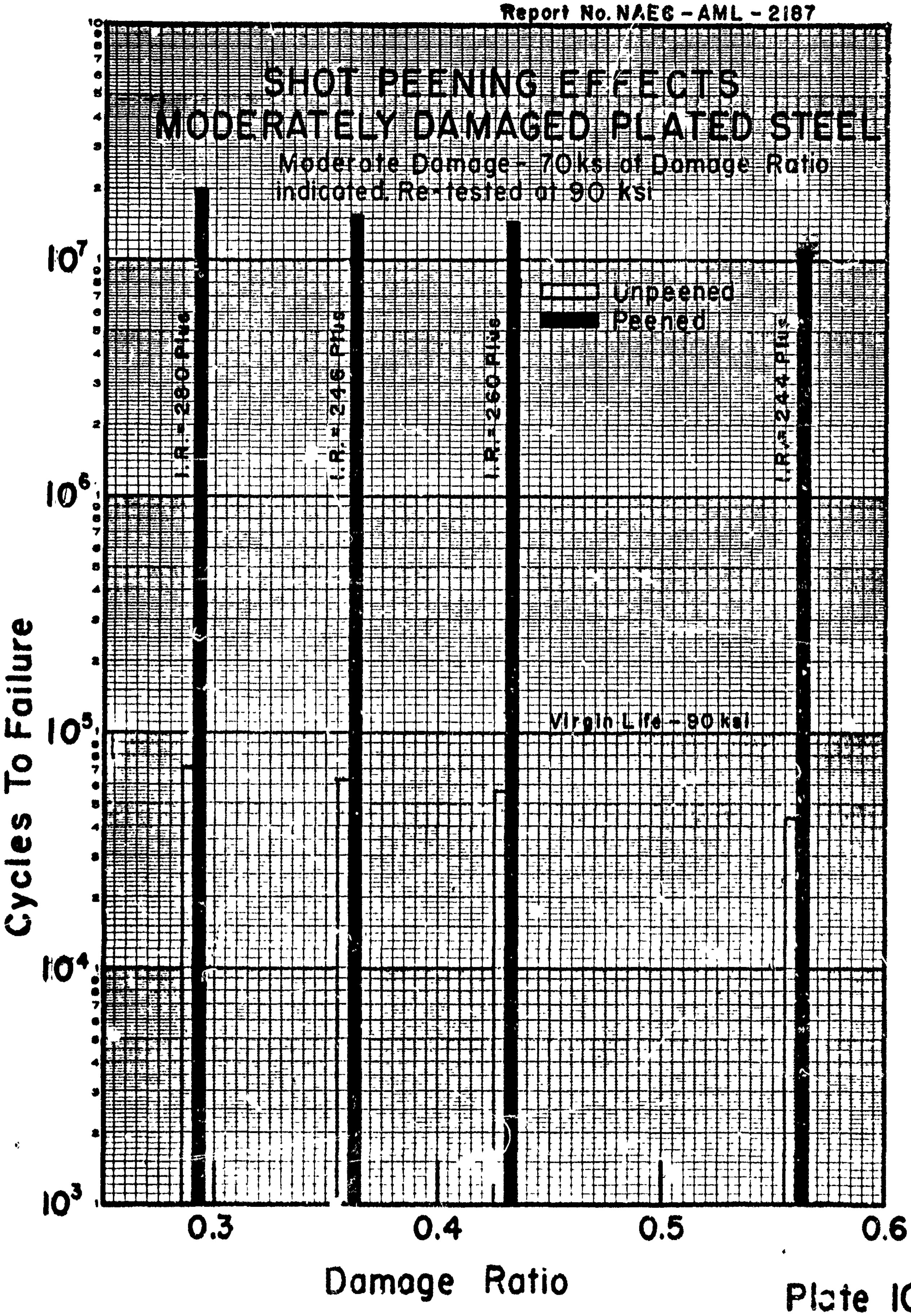

SHOT PEENING EFFECTS
SEVERELY DAMAGED PLATED STEEL
Severe Damage - 100ksi at Damage Ratio indicated. Retested at 90 Ksi.
Unpeened
Peened
I.R. = 400 Plus
I.R. = 468 Plus
I.R. = 2.1
I.R. = 2.2
I.R. = 2.0
I.R. = 0.6
Virgin Life - 90 ksi
Cycles To Failure
10^7
10^6
10^5
10^4
10^3
0.5
0.6
0.7
0.8
0.9
1.0
Damage Ratio

Plate 9


SHOT PEENING EFFECTS
MODERATELY DAMAGED PLATED STEEL
Moderate Damage - 70 ksi at Damage Ratio indicated. Re-tested at 90 ksi
Unpeened
Peened
I.R. = 280 Plus
I.R. = 246 Plus
I.R. = 260 Plus
I.R. = 244 Plus
Virgin Life - 90 ksi
Cycles To Failure
10^7
10^6
10^5
10^4
10^3
0.3
0.4
0.5
0.6
Damage Ratio

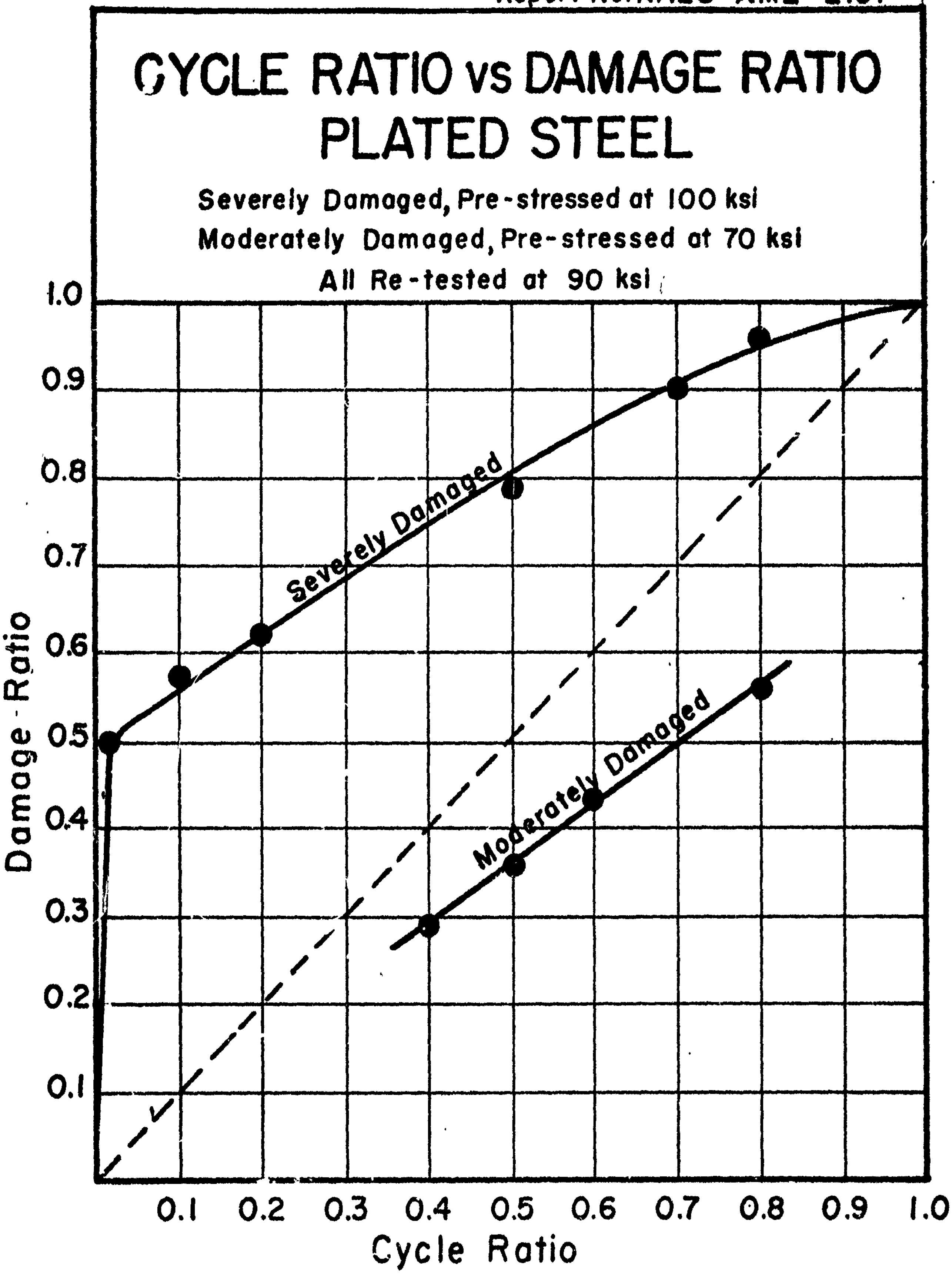
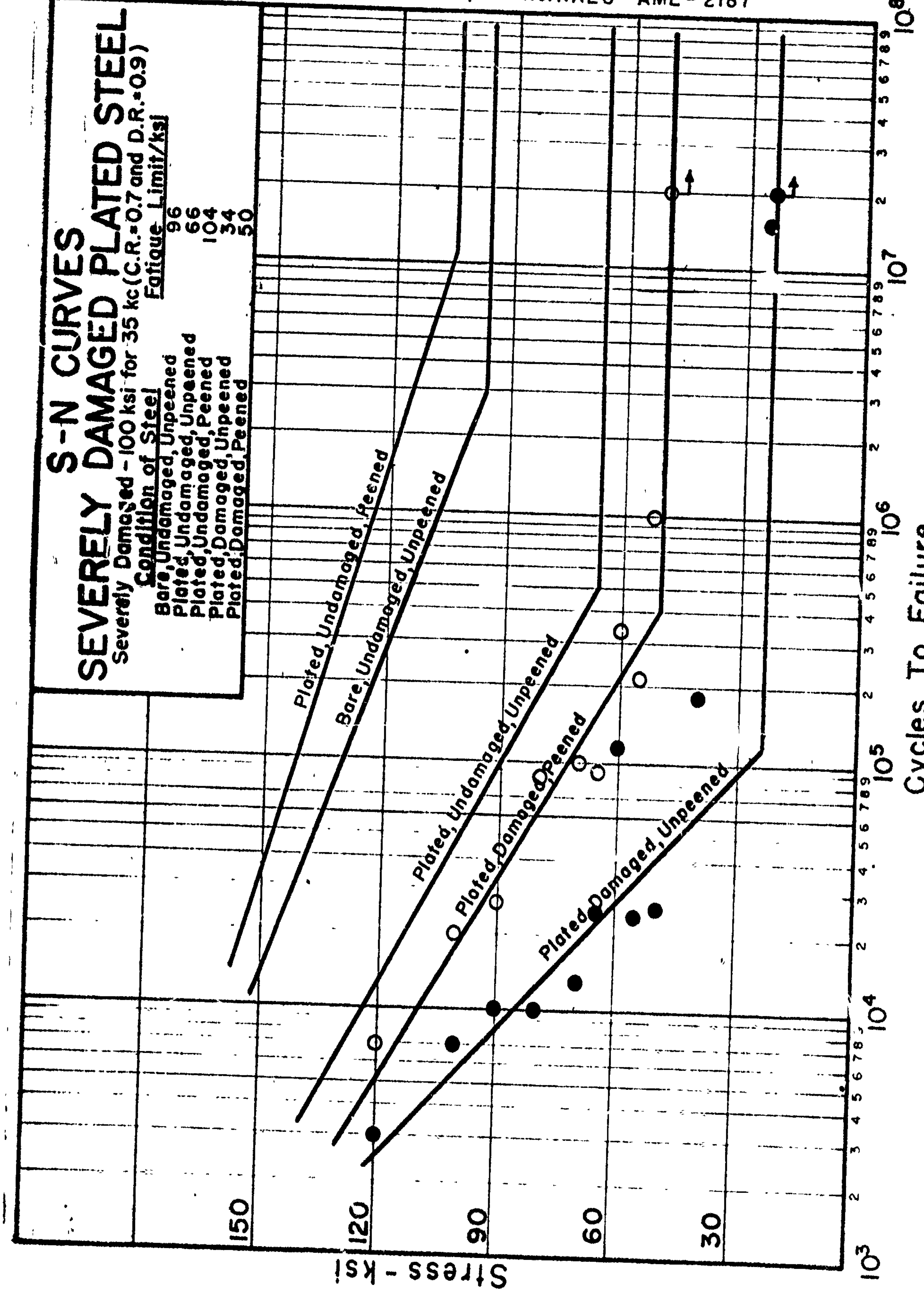
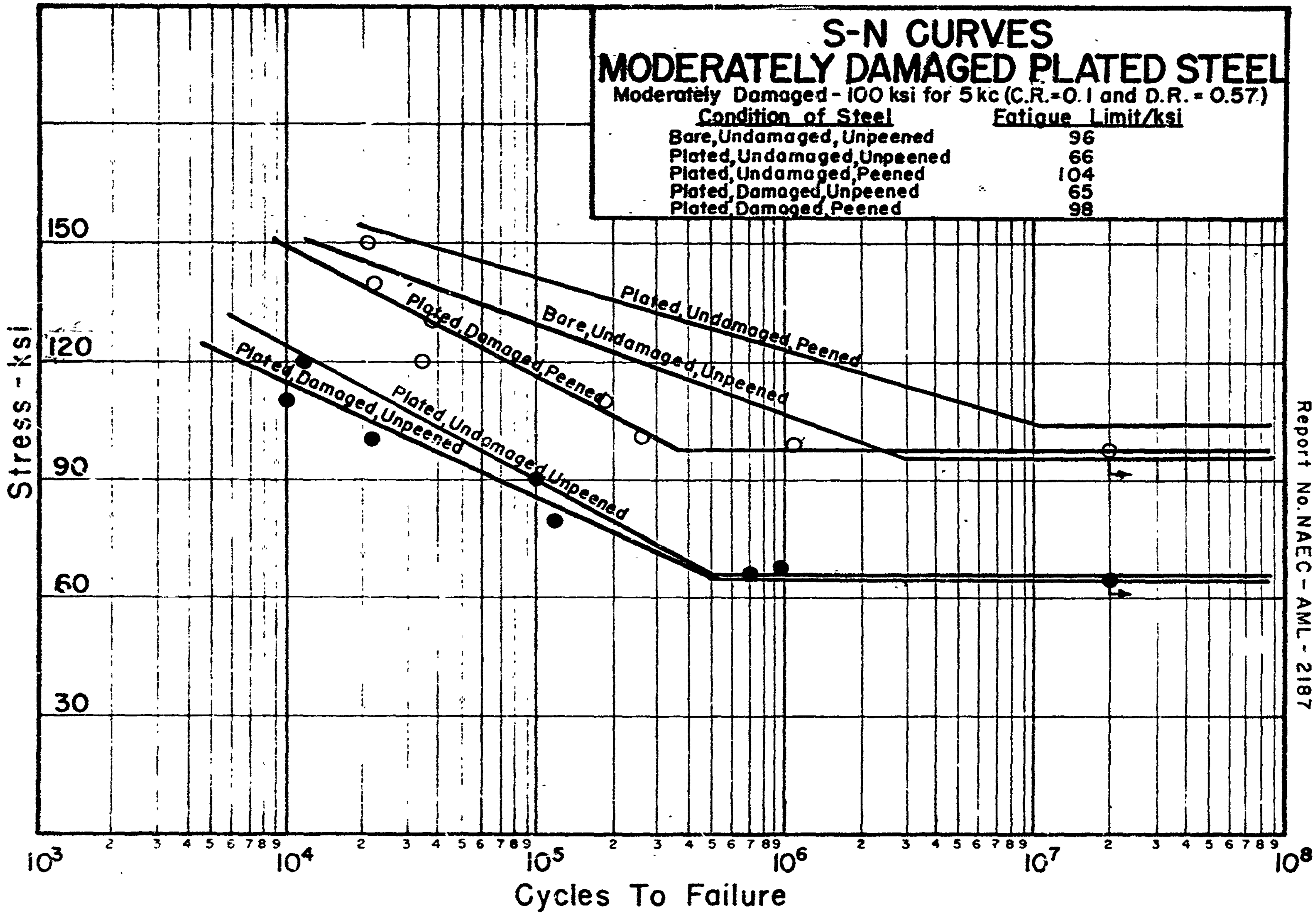

CYCLE RATIO vs DAMAGE RATIO
PLATED STEEL
Severely Damaged, Pre-stressed at 100 ksi
Moderately Damaged, Pre-stressed at 70 ksi
All Re-tested at 90 ksi
Severely Damaged
Moderately Damaged
Damage - Ratio
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Cycle Ratio

Plate II


S-N CURVES
SEVERELY DAMAGED PLATED STEEL
Severely Damaged - 100 ksi for 35 kc (C.R.=0.7 and D.R.=0.9)
Condition of Steel
Fatigue Limit/ksi
Bare, Undamaged, Unpeened 96
Plated, Undamaged, Unpeened 66
Plated, Undamaged, Peened 104
Plated, Damaged, Unpeened 34
Plated, Damaged, Peened 50
Plated, Undamaged, Peened
Bare, Undamaged, Unpeened
Plated, Undamaged, Unpeened
Plated, Damaged, Peened
Plated, Damaged, Unpeened
150
120
90
60
30
Stress - ksi
10^3
10^4
10^5
10^6
10^7
10^8
Cycles To Failure


S-N CURVES
MODERATELY DAMAGED PLATED STEEL
Moderately Damaged - 100 ksi for 5 kc (C.R. = 0.1 and D.R. = 0.57)
Condition of Steel
Fatigue Limit/ksi
Bare, Undamaged, Unpeened 96
Plated, Undamaged, Unpeened 66
Plated, Undamaged, Peened 104
Plated, Damaged, Unpeened 65
Plated, Damaged, Peened 98
Plated, Undamaged, Peened
Bare, Undamaged, Unpeened
Plated, Damaged, Peened
Plated, Undamaged, Unpeened
Plated, Damaged, Unpeened
Stress - ksi
150
120
90
60
30
10^3
10^4
10^5
10^6
10^7
10^8
Cycles To Failure

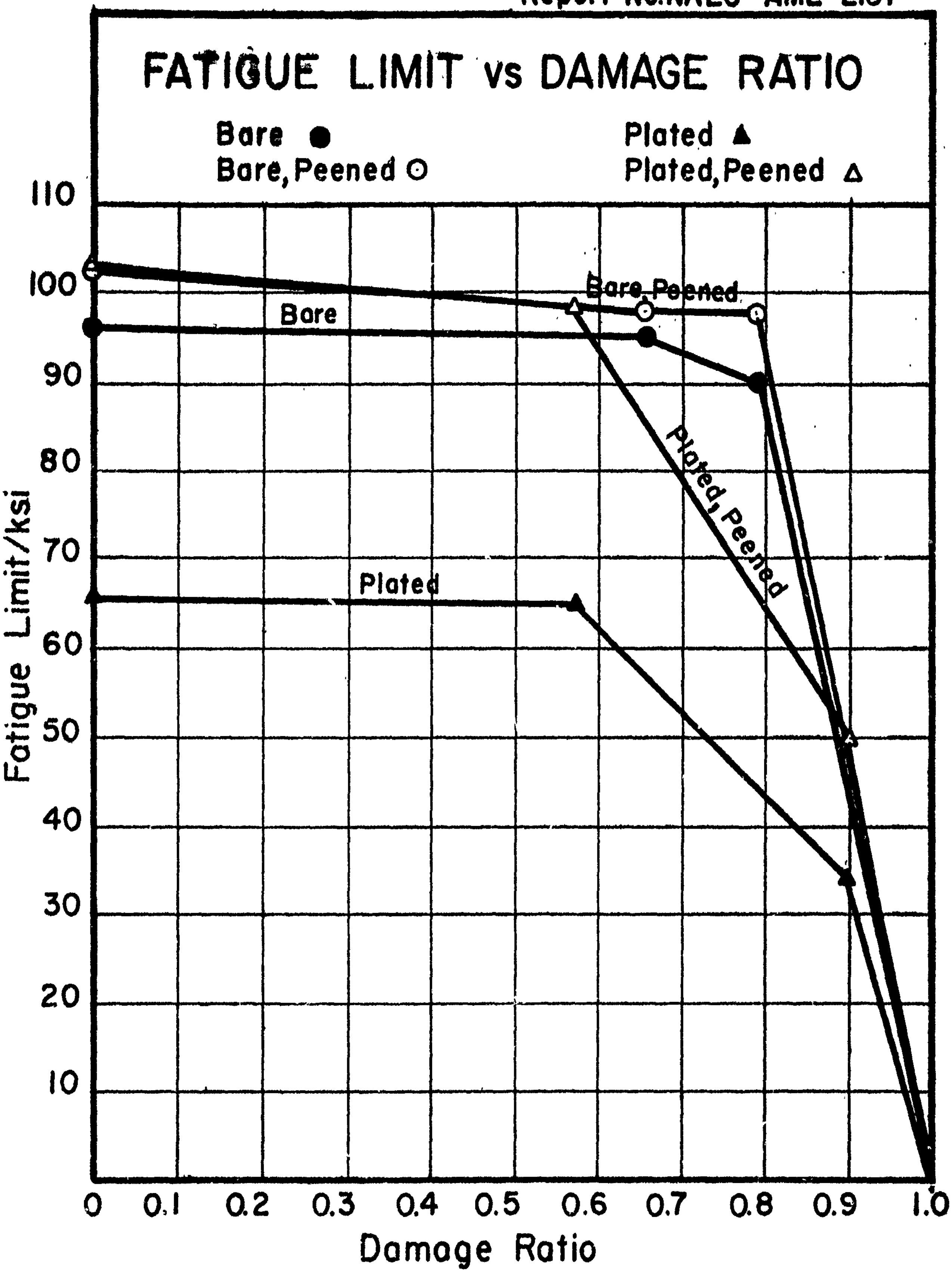

FATIGUE LIMIT vs DAMAGE RATIO
Bare
Bare, Peened
Plated
Plated, Peened
110
100
90
80
70
60
50
40
30
20
10
Fatigue Limit/ksi
Bare, Peened
Bare
Plated, Peened
Plated
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Damage Ratio

Plate 14

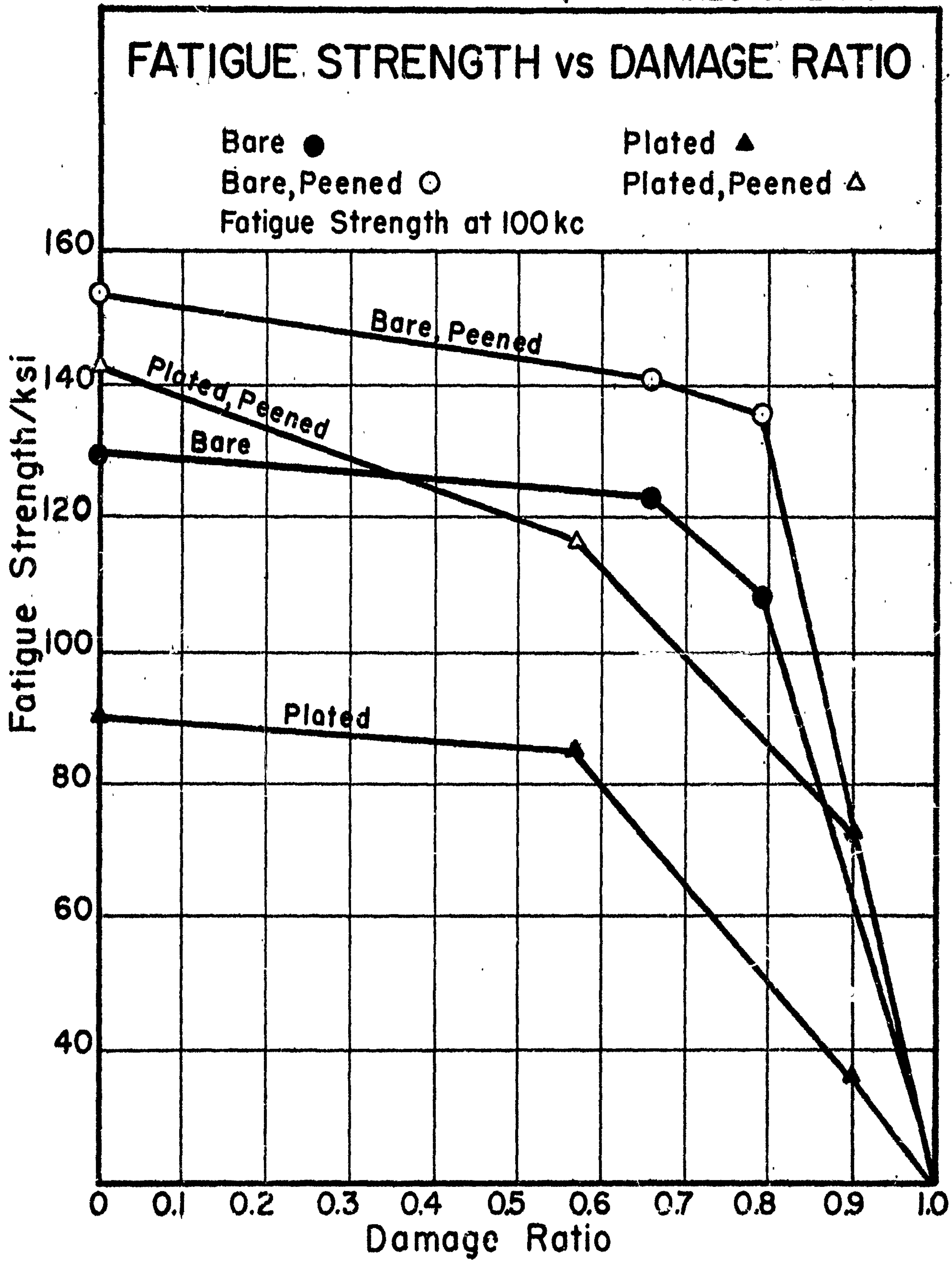
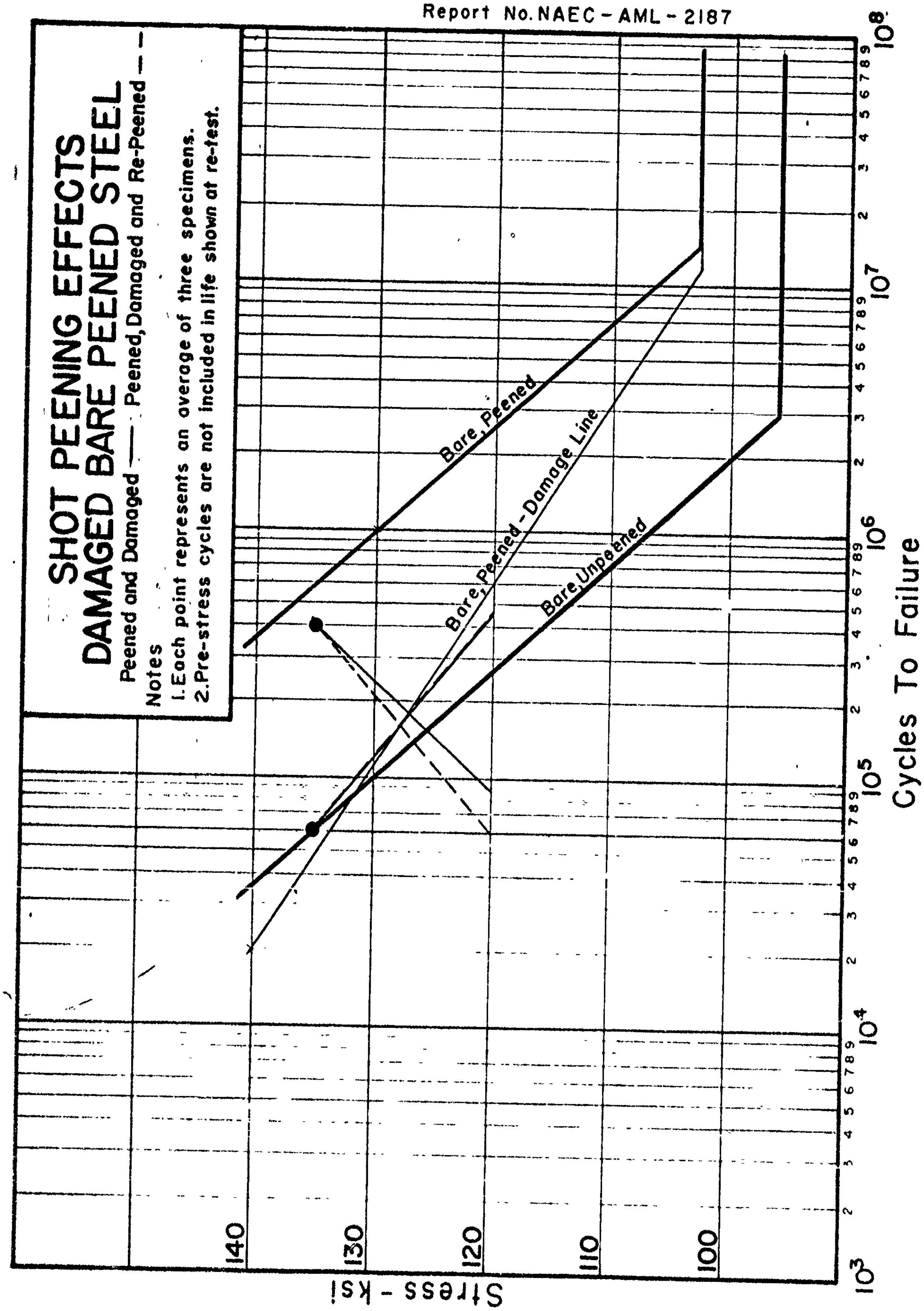
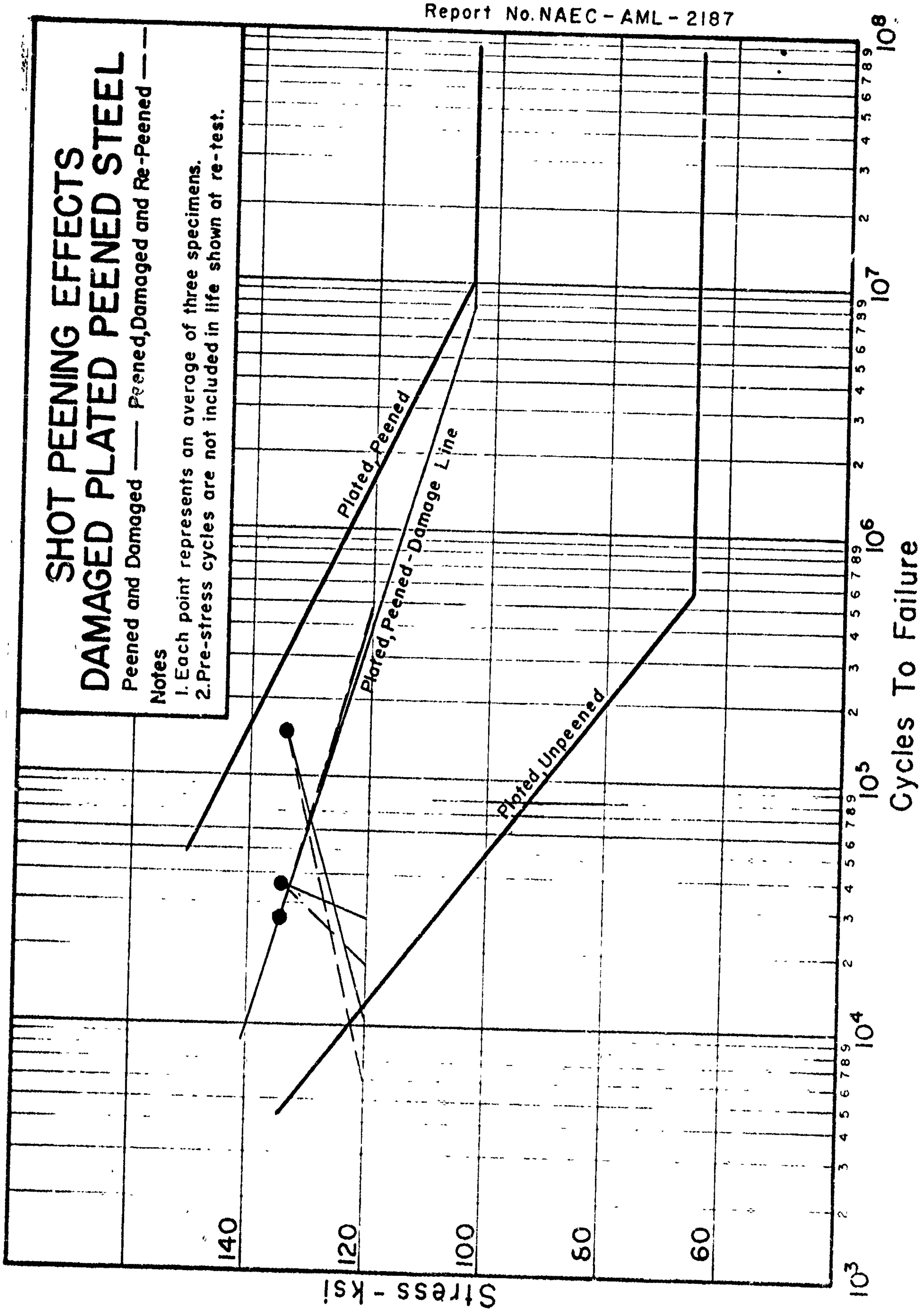
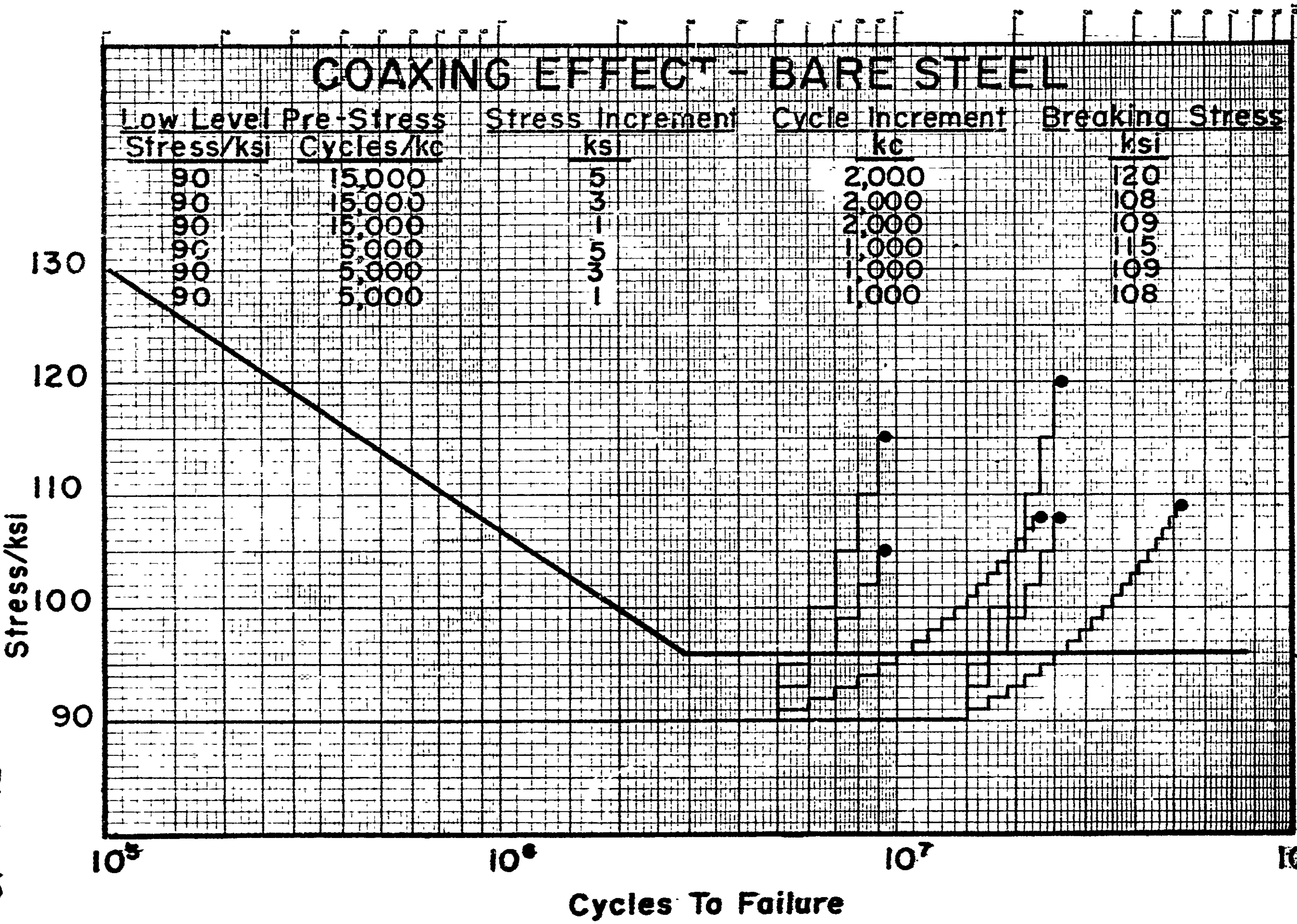

FATIGUE STRENGTH vs DAMAGE RATIO
Bare ●
Plated ▲
Bare, Peened ⊙
Plated, Peened △
Fatigue Strength at 100 kc
Bare, Peened
Plated, Peened
Bare
Plated
Fatigue Strength/ksi
160
140
120
100
80
60
40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Damage Ratio

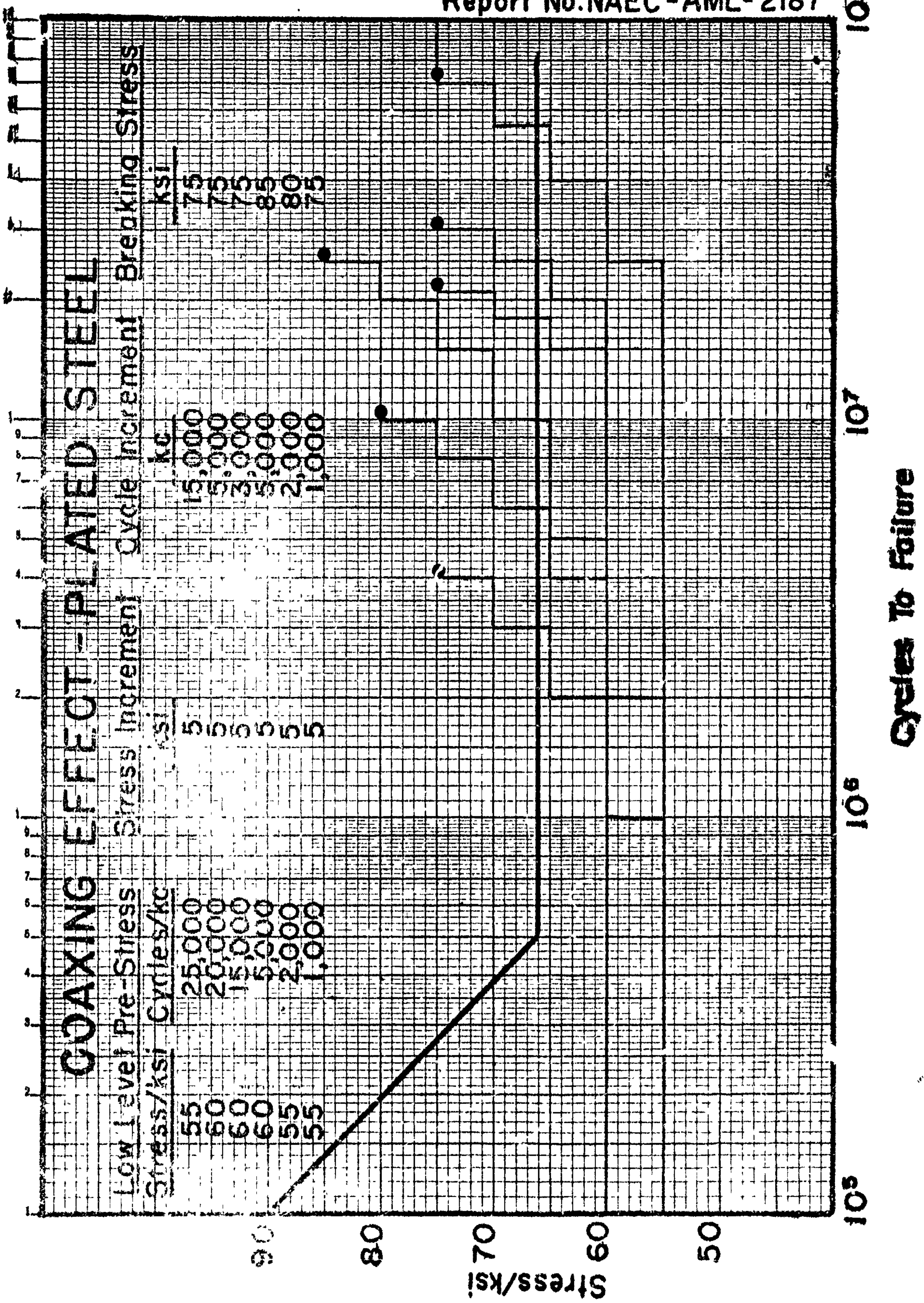
Plate 15



SHOT PEENING EFFECTS
DAMAGED BARE PEENED STEEL
Peened and Damaged —— Peened, Damaged and Re-Peened — —
Notes
1. Each point represents an average of three specimens.
2. Pre-stress cycles are not included in life shown at re-test.
Bare, Peened
Bare, Peened-Damage Line
Bare, Unpeened
Stress - ksi
140
130
120
110
100
Cycles To Failure
10^3
10^4
10^5
10^6
10^7
10^8


SHOT PEENING EFFECTS
DAMAGED PLATED PEENED STEEL
Peened and Damaged ——— Peened, Damaged and Re-Peened - - -
Notes
1. Each point represents an average of three specimens.
2. Pre-stress cycles are not included in life shown at re-test.
Plated, Peened
Plated, Peened-Damage Line
Plated, Unpeened
Stress - ksi
140
120
100
80
60
Cycles To Failure
10^3
10^4
10^5
10^6
10^7
10^8


COAXING EFFECT - BARE STEEL
Low Level Pre-Stress
Stress/ksi
Cycles/kc
Stress Increment
ksi
Cycle Increment
kc
Breaking Stress
ksi
90 15,000 5 2,000 120
90 15,000 3 2,000 108
90 15,000 1 2,000 109
90 5,000 5 1,000 115
90 5,000 3 1,000 109
90 5,000 1 1,000 108
130
120
110
100
90
Stress/ksi
10^5
10^6
10^7
10^8
Cycles To Failure


COAXING EFFECT - PLATED STEEL
Low Level Pre-Stress
Stress/Ksi Cycles/kc
55 25,000
60 20,000
60 15,000
60 5,000
55 2,000
55 1,000
Stress Increment
Ksi
5
5
5
5
5
5
Cycle Increment
kc
15,000
5,000
3,000
5,000
2,000
1,000
Breaking Stress
Ksi
75
75
75
85
80
75
Stress/Ksi
90
80
70
60
50
Cycles To Failure
10^5
10^6
10^7
10^8

U. S. NAVAL AIR ENGINEERING CENTER
AERONAUTICAL MATERIALS LABORATORY
PHILADELPHIA, PA. 19112

1. Report No. NAEC-AML-2187
2. PAN 12-28

The Effects of Shot Peening on the Fatigue Properties of Damaged Bare and Damaged Chrome Plated High Strength 4340 Steel; J. Viglione, July 1965, 23 pages, 7 tables, 19 plates

It was determined that shot peening has a significant beneficial effect on the fatigue properties of damaged bare and damaged plated 4340 steel (260 ksi), particularly upon the fatigue life at stresses above the fatigue limit. It was further established that shot peening is more beneficial in recovery of mild damage than it is in the recovery of severe damage. There are indications that shot peening of steel damaged to an extremely severe degree has a further deleterious effect on the fatigue properties of the damaged steel.

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ABSTRACT CARD OFFSET MARGINAL GUIDE
NND-NANC-5602/1